Resources and ISRU from the Martian Subsurface

Feb. 12, 2018

Presentation to Keck Institute of Space Studies (KISS)
for
MarsX: Mars Subsurface Exploration Study

Gerald (Jerry) Sanders
Lead for NASA ISRU System Capability Leadership Team
NASA Johnson Space Center, Houston, TX,

Presentation Overview

- What is In Situ Resource Utilization (ISRU) and Why Incorporate it into Missions?
- Available Resources and Locations of Interest
- Challenges and Risks for ISRU
- Concepts of Operation for Water-based ISRU on Mars
- Mars Water ISRU and Connection to Planetary Protection & Search for Life

What is
In Situ Resource Utilization (ISRU)
and
Why Use It in Missions?

What is *In Situ* Resource Utilization (ISRU)?

ISRU involves any hardware or operation that harnesses and utilizes 'in-situ' resources to create products and services for robotic and human exploration

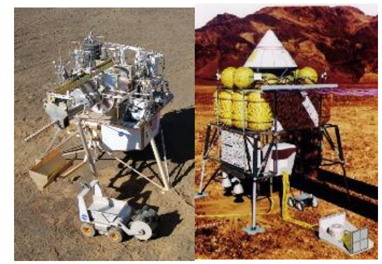
Resource Assessment (Prospecting)

Assessment and mapping of physical, mineral, chemical, and water resources, terrain, geology, and environment

Resource Acquisition

Atmosphere constituent collection, and material/volatile collection via drilling, excavation, transfer, and/or manipulation before Processing

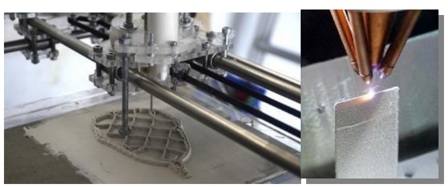
Resource Processing/ Consumable Production



Conversion of acquired resources into products with immediate use or as feedstock for construction & manufacturing

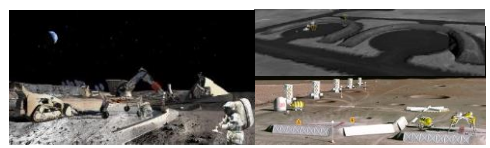
- Propellants, life support gases, fuel cell reactants, etc.

In Situ Manufacturing



Production of replacement parts, complex products, machines, and integrated systems from feedstock derived from one or more processed resources

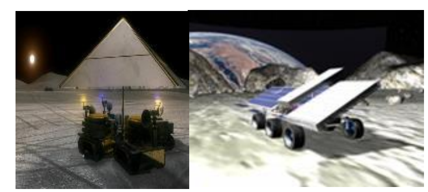
In Situ Construction



Civil engineering, infrastructure emplacement and structure construction using materials produced from *in situ* resources

- Radiation shields, landing pads, roads, berms, habitats, etc.

In Situ Energy



Generation and storage of electrical, thermal, and chemical energy with *in situ* derived materials

- Solar arrays, thermal storage and energy, chemical batteries, etc.

- **'ISRU' is a capability involving multiple elements to achieve final products** (mobility, product storage and delivery, power, crew and/or robotic maintenance, etc.)
- **'ISRU' does not exist on its own.** By definition it must connect and tie to users/customers of ISRU products and services

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Primary focus of KISS MarsX Study

In Situ Manufacturing

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G. Sanders, (281) 483-9066, gerald.b.sanders@nasa.gov

Architecture Benefits/Solutions Provided by ISRU

Enablers for Human Mars Exploration

Increase Sustainability/Decreases Life Cycle Costs

- Reduce launch mass and/or number of launchers required
- Reuse landers and transportation elements can provide significant cost savings
- Growth in capabilities in life support, habitats, powers, etc.
- Enables path for commercial involvement and investment

Increase Mission Performance and Capabilities

- Longer stays, increased EVA, or increased crew over baseline with ISRU consumables
- Increased payload-to-orbit or delta-V for faster rendezvous with fueling of ascent vehicle
- Increased and more efficient surface nighttime and mobile fuel cell power architecture with ISRU
- Decreased logistics and spares brought from Earth

Reduce Mission and Crew Risks

- Minimizes/eliminates life support consumable delivery from Earth
- Increases crew radiation protection over Earth delivered options
- Can relax critical requirements in other system performance
- Minimizes/eliminates ascent propellant boiloff leakage issues
- Minimizes/eliminates landing plume debris damage – Civil engineering and construction

Increases Science

- Greater surface and science sample collection access thru in-situ fueled hoppers
- Greater access to subsurface samples thru ISRU excavation and trenching capabilities
- Increased science payload per mission by eliminating consumable delivery

Supports Multiple Destinations

- Surface soil processing operations associated with ISRU applicable to Moon and Mars
- ISRU subsystems and technologies are applicable to multiple destinations and other applications
- Resource assessment for water/ice and minerals common to Moon, Mars, and NEOs

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Architecture Benefits/Solutions Provided by ISRU

Extra Benefits with Water Resources

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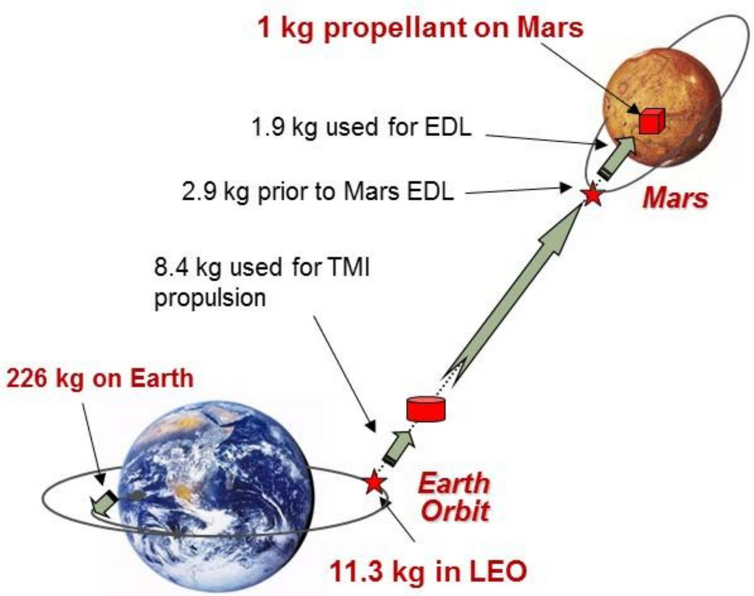
Main Advantage of ISRU over Earth Delivered Products – Launch Mass Reduction (Gear Ratio)

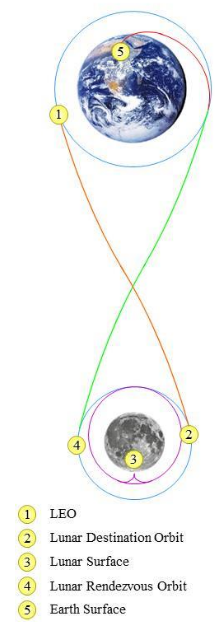
Every 1 kg of propellant made on the Moon or Mars saves 7.4 to 11.3 kg in LEO

Potential 334.5 mT launch mass saved in LEO = 3 to 5 SLS launches avoided per Mars Ascent

- **Mars mission**
  - Oxygen only — 75% of ascent propellant mass; 20 to 23 mT
  - Methane + Oxygen — 100% of ascent propellant mass: 25.7 to 29.6 mT
    Regeneration of rover fuel cell reactant mass
- **Phobos mission**
  - Trash to O_2/CH_4 — 1000+ kg of propellant



Estimates based on Aerocapture at Mars



A Kilogram of Mass Delivered Here…	…Adds This Much Initial Architecture Mass in LEO	…Adds This Much To the Launch Pad Mass
Ground to LEO	-	20.4 kg
LEO to Lunar Orbit (#1→#2)	4.3 kg	87.7 kg
LEO to Lunar Surface (#1→#3; e.g., Descent Stage)	7.5 kg	153 kg
LEO to Lunar Orbit to Earth Surface (#1→#4→#5; e.g., Orion Crew Module)	9.0 kg	183.6 kg
Lunar Surface to Earth Surface (#3→#5; e.g., Lunar Sample)	12.0 kg	244.8 kg
LEO to Lunar Surface to Lunar Orbit (#1→#3→#4; e.g., Ascent Stage)	14.7 kg	300 kg
LEO to Lunar Surface to Earth Surface (#1→#3→#5; e.g., Crew)	19.4 kg	395.8 kg

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Mars Consumable Production Requirements

The 2 Driving Requirements for ISRU are Amount Needed & Time Available

3.1 Amount Requirements (purpose, customer, amounts)

	NASA Reference Architectures				Mars ISRU Studies & Calculations				
	DRM 1.0	DRM 3.0	DRA 5.0	EMC ISRU	FC Powered Rover Study (14 day ops)	Hab. FC Power Backup (14.8 KW - 120 days)	Hercules Reusable Lander^	Mars Water Rich Study#	ISRU AES/STMD FY17
O_2 for Ascent Prop (kg)	83,500	30,333	22,985	22,728*			59,004	29,758	22,728*
O_2 for Life Support (kg)		4500	1906 (O_2 only)						See water
O_2 for FC Power					1000	21,000		30,276	TBD-SaWS
CH_4 for Ascent Prop. (kg)	23,200	8667	6250	6978*			17,102	8,748	6978*
CH_4 for FC Power					350	9,000		9,936	TBD-SaWS
N_2 for Life Support (kg)		3900	133						136^^
H_2O for Life Support/EVA (kg)		23,200	3192	3072 (EVA)**				24,379	4050 Closure/EVA#
H_2 Brought from Earth	5800	5420	399 (O_2 only)						0

Notes
*Mars Ascent Vehicle (Polsgrove AIAA 2015)
**FY16 EMC TIV Sep Briefing Task 11 ISRU
^Sustainable Human Presence on Mars Using ISRU and a Reusable Lander (Arney, Moses, et. al)
#A Water Rich Mars Surface Mission Scenario (978-1-5090-1613-6/17/$31.00 ©2017 IEEE)
^^Email from Dan Barta 7/31/17

= Initial Requirements
= Horizon Goals

3.2 Time Requirements

- DRM 3.0/DRA 5.0): ISRU must complete production before crew leaves Earth
- EMC: ISRU must complete production before crew leaves Earth OR before crew descends to surface (depending on mission arch.)

	NASA Reference Architectures				Mars ISRU Studies & Calculations		
	DRM 3.0	DRA 5.0**	EMC ISRU	EMC GR&A***	FC Powered Rover Study (14 day ops)	Hercules Reusable Lander^	ISRU AES/STMD FY17
A. Time between ISRU Landing & Crew Leaving Earth (days)*	520	330				520	540
B. Contingency: Failures/dust storms (days)	40	30				40	See ISRU Tech Project Requirements 5-12-17
Production duration (= A – B)	480	300	480	>14 mo. min (420 days) for SEP-Chem. >18 mo. min (540 days) for Hybrid	30 (1 trip per month)	480 (1/op) 365 (1/yr) 183 (2/yr)	See ISRU Tech Project Requirements 5-12-17
ISRU Hardware Life: Days	▪ 480 min. ▪ Additional 240 days for life support consumables (between crew Earth departure & Mars arrival)	▪ 480 min. ▪ 1200 desired for additional operation through end of crew stay	▪ 480 min. ▪ Additional operation desired but not specified				540 min without maintanance
Operating Cycle Life			▪ 40^				40 nuc 540 max solar

Notes:
*Since launch dates/trajectories are based on the Earth calendar, mission durations are in Earth days (24 hrs) vs Mars sols. The amount of time also changes each opportunity due to variations in Mars eccentric orbit compared to Earth's
**Duration should have been similar to DRM 3.0. Unknown reason why the duration was reduced.
***Integration F2F Outbrief 6-9-2016v5.ppt
^Linne, et. al, "Capability and Technology Performance Goals for the Next Step in Affordable Human Exploration of Space", AIAA SciTech, Jan. 2015.

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2017 ISRU Mars ISRU Case Study & Variables*

Methane & Oxygen ISRU *(soil water + atmosphere processing)*	**vs**	**Oxygen Only ISRU** *(atmospheric processing)*
Ascent Propellant Production	**vs**	**Ascent Propellants + Life support Consumables**
Low Yield Regolith *(Ubiquitous)*	**vs**	**High Yield Surface Regolith** *(Localized)*

- **Oxygen Only ISRU:**
  - As called out in DRA 5.0
  - Using Solid Oxide Electrolysis
  - Full system model

ISRU O_2		ISRU CH_4	ISRU H_2O	
Ascent Propellant	Life Support	Ascent Propellant	Processed into O_2 & CH_4	Life Support
22728 kg	1906 kg	6978 kg	18891 kg	24179 kg

- **Life Support Consumables****
  - Most conservative case, assumes highly 'water rich' scenario
    - Open loop ECLSS
    - Mars water use for everything from drinking water to Laundry.

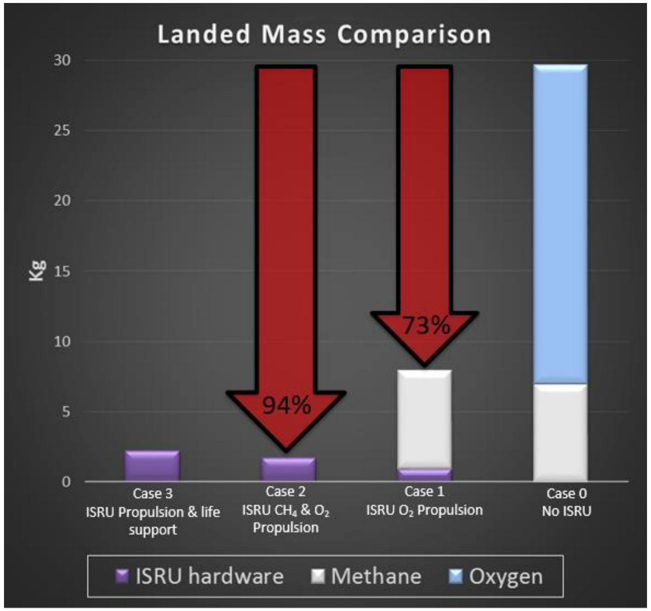
*Julie Kleinhenz, Aaron Paz, "An ISRU Propellant Production System to Fully Fuel a Mars Ascent Vehicle", AIAA SciTech Conf., Orlando, FL, Jan. 2017

**Stephen J. Hoffman, Alida Andrews, B. Kent Joosten, Kevin Watts, "A Water-Rich Mars Surface Mission Scenario", to be published IEEE-2422, *IEEE Aerospace Conference*, Big Sky, MO, March 4-11, 2017

Example of Benefit of ISRU: Mars ISRU Study - Mass Result Comparison

	ISRU system Landed Mass Comparison (ISRU Hardware + Propellant from Earth)		
	The ISRU system leverages the power and radiator systems that are pre-positioned by the lander for human systems. So these are not explicitly part of the ISRU system.		
	ISRU Hardware Mass, mT	Total Mass, mT	Production Ratio: Propellant produced per kg of total mass
Case 3 ISRU propellants, & life support	2.2	2.2	13.5
Case 2 ISRU propellants, baseline regolith	1.7	1.7	17.7
Case 1 ISRU O_2 propellant	0.93	8.0 (1mt hardware + 7mt Methane)	2.9
Case 0 No ISRU	0	29.7 (23mt Oxygen + 7mt Methane)	na

- **The addition of methane production increases ISRU mass 1 mT over the oxygen-only case assuming the lowest yield regolith**
- **Total mass considers ascent propellant mass transported from Earth. However producing that propellant in-situ will save additional mass not estimated:**
  - Propellant and hardware required to deliver hardware and ascent propellants from LEO
  - EDL systems to land the ascent propellant
- **Propellant production Ratio = Mass Propellant Produced / Hardware mass**
  - Full ISRU offers a 6x improvement over oxygen-only ISRU using the lowest yield regolith

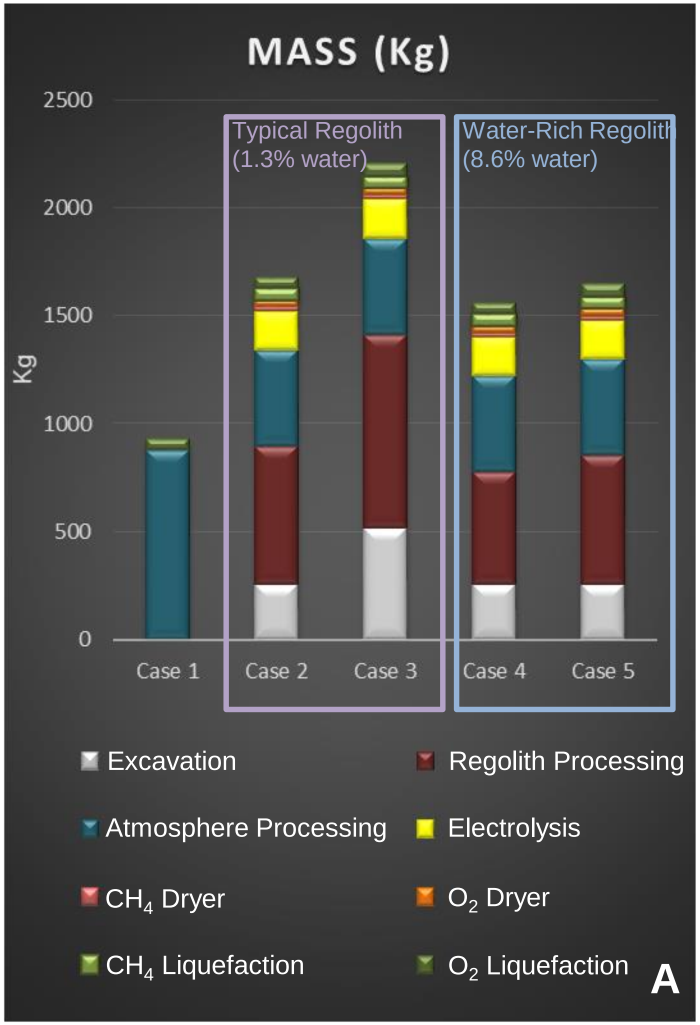


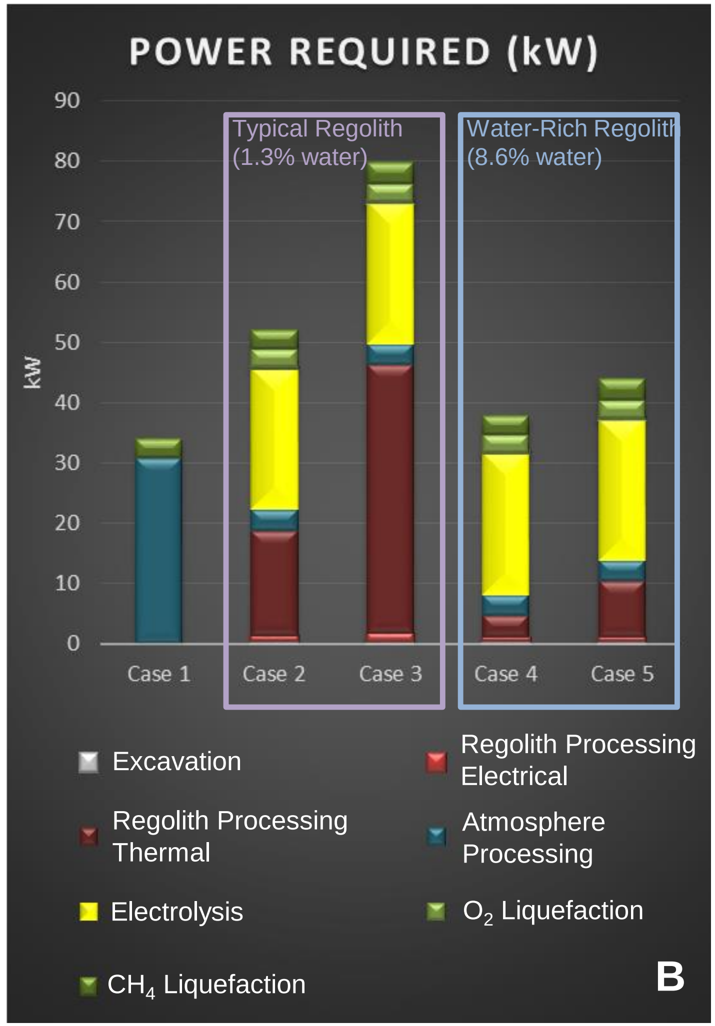
- **Mass savings in LEO is ~10 kg per 1 kg of propellant produced**
  - LEO Mass savings on the order of 300 mT with full ISRU system
  - Reduces cost and eliminates several heavy lift launch vehicles

Mars ISRU Study Results: All Trades

For 1.3 and 8.6 wt% Water Hydrated Resources

Case 1	Case 2 + 4	Case 3 + 5
Oxygen propellant	Ascent Propellants	Ascent Propellants + Life Support water





Case 2 vs 3

- Only impacts excavators and regolith processor subsystems
- Size of regolith processors
- Number of excavators

Power

- Thermal heat could be provided by recuperation

Higher Yield regolith

- The addition of life support consumables has only marginal impact on mass and power
- Due to decrease in processing temperature, power levels are comparable to Oxygen-only case
- Larger mass reduction (25%) due to fewer excavators

Conclusion – Human Mars Surface Missions Need to Exploit Mars Water Resources

Water on Mars is Abundant (see next section)

- Low weight percent water (1 to 3%) exists in granular soils at the surface almost everywhere on Mars
- Much higher weight percent water (5 to 12%) exists in hydrated minerals at sites of high scientific interest (ex. Mars 2020 & ExoMars sites)
- Near subsurface ice sheets exist at mid-upper latitudes (>40 to 60 deg.)

Water Resources provide <u>significant</u> benefits for human Mars exploration

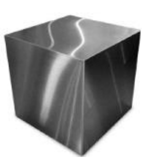
- Overall launch and mission mass reduction for Mars
- Enables reusability of transportation elements; landers/ascent and hoppers
- Enables and grows fuel cell power infrastructure
- Increased radiation protection: water walls; ice house
- Greater number of secondary products: plastics, solvents, construction materials
- Dissimilar backup/redundancy to life support systems; less need for full life support closure
- Food growth/hydroponics and fish/animal husbandry support

Even low concentration water resources can provide significant mass and mission benefits

- Higher concentrations reduce mass, power, and hardware life risks

Available Resources and Locations of Interest

Main *Natural* Space Resources of Interest

	 Moon	 Mars	 Asteroids	Uses
Water	Icy Regolith in Permanently Shadowed Regions (PSR) Solar wind hydrogen with Oxygen	Hydrated Soils/Minerals: Gypsum, Jarosite, Phylosilicates, Polyhdrated Sulfates Subsurface Icy Soils in Mid-latitudes to Poles	Subsurface Regolith on C-type Carbonaceous Chondrites	▪ Drinking, radiation shielding, plant growth, cleaning & washing ▪ Making Oxygen and Hydrogen
Oxygen 	Minerals in Lunar Regolith: Ilmenite, Pyroxene, Olivine, Anorthite	Carbon Dioxide in the atmosphere (~96%)	Minerals in Regolith on S-type Ordinary and Enstatite Chondrites	▪ Breathing ▪ Oxidizer for Propulsion and Power
Carbon 	▪ CO, CO_2, and HC's in PSR ▪ Solar Wind from Sun (~50 ppm)	Carbon Dioxide in the atmosphere (~96%)	Hydrocarbons and Tars (PAHs) in Regolith on C-type Carbonaceous Chondrites	▪ Fuel Production for Propulsion and Power ▪ Plastic and Petrochemical Production
Metals 	Minerals in Lunar Regolith ▪ Iron/Ti: Ilmenite ▪ Silicon: Pyroxene, Olivine, Anorthite ▪ Magnesium: Mg-rich Silicates ▪ Al:: Anorthitic Plagioclase	Minerals in Mars Soils/Rocks ▪ Iron: Ilmenite, Hematite, Magnetite, Jarosite, Smectite ▪ Silicon: Silica, Phyllosilicates ▪ Aluminum: Laterites, Aluminosilicates, Plagioclase ▪ Magnesium: Mg-sulfates, Carbonates, & Smectites, Mg-rich Olivine	Minerals in Regolith/Rocks on S-type Stony Iron and M-type Metal Asteroids	▪ *In situ* fabrication of parts ▪ Electical power transmission

Similar Resources and Needs Exist at Multiple Locations

Mars Resources

Atmosphere

- Pressure: 6 to 10 torr (~0.08 to 0.1 psi);
- Temperature: +35 °C to -125 °C
- Constituents: 95.32% Carbon Dioxide (CO_2); 2.7% Nitrogen (N_2); 1.6% Argon (Ar); 0.13% Oxygen (O_2); 0.08% Water (H_2O)

Resource	Potential Mineral Source		Reference
Water, Hydration/ Hydroxyl	Gypsum – ($CaSO_4.2H_2O$) Jarosite – ($KFe^{3+}{}_3(OH)_6(SO4)_2$) Opal & hydrated silica – ($SiO_2.nH_2O$) Phyllosilicates Other hydrated minerals (TBR)		Horgan, et al.(2009), Distribution of hydrated minerals in the north polar region of Mars, J. Geophys. Res., 114, E01005 Mustard et al.(2008), Hydrated silicate minerals on Mars observed by the Mars Reconnaissance Orbiter CRISM instrument, Nature 454, 305-309
Water, Ice	Icy soils Glacial deposits		Mellon & Feldman (2006) Dickson et al. (2012)
Iron*	Hematite Magnetite Laterites	Jarosite Triolite Ilmenite	Ming et al. (2006), Geochemical and mineralogical indicators for Aqueous processes in Columbia Hills of Gusev Crater, Mars" JGR 111, E02S12 Poulet et al. (2007), Martian surface mineralogy from OMEGA/Mex: Global mineral maps" JGR 112, E08S02
Aluminum*	Laterites Aluminosilicates	Plagioclase Scapolite	
Magnesium*	Mg-sulfates, Mg-rich olivines, Forsterite		
Silicon	Pure amorphous silica Hydrated silica Phyllosilicates		Rice et al. (2010), "Silica-rich deposits and hydrated minerals at Gusev Crater, Mars: Vis-NIR spectral characterization and regional mapping" Icarus 205 (2010) 375–395
Titanium*	Ilmenite, Titanomagnetite		Ming et al. (2006), JGR 111, E02512

	Oxides (Wt%)													Elements (ppm)			
	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Cr_2O_3	Cl	SO_3	Ni	Zn	Br	Ge
MER Spirit – Laguna Soils, Panda Subclass	46.8	0.79	10.5	16.1	0.33	9.6	6.2	3	0.38	0.75	0.35	0.6	4.6	684	190	42	6
Rocknest Soil (Portage)	43.0	1.2	9.4	19.2	0.42	8.7	7.3	2.7	0.49	0.95	0.49	0.69	5.5	456	326	34	
Mojave Mars Simulant	49.4	1.09	17.1		0.17	6.1	10.5	3.3	0.48	0.17	0.05		0.1	118	71		0.07

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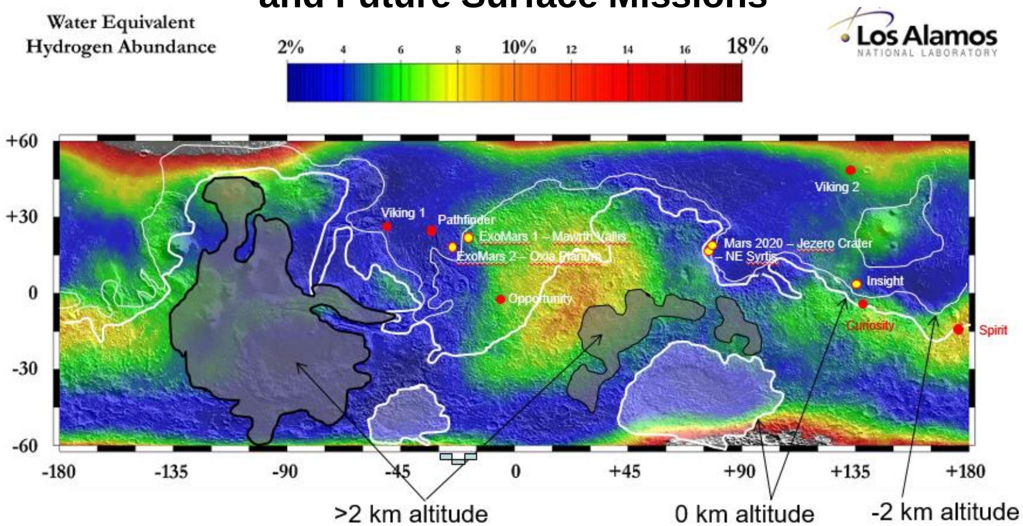
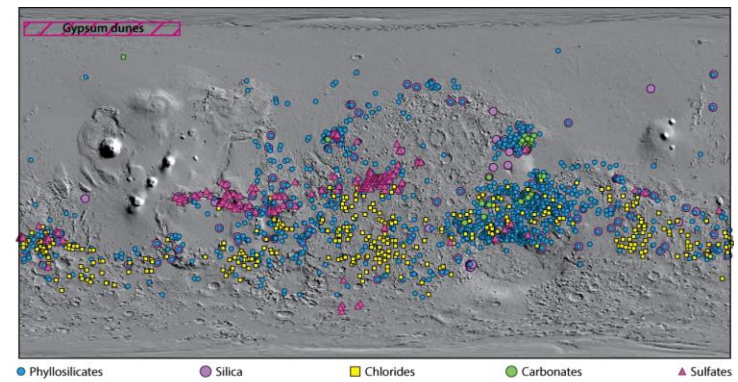
Mars Water Form & Distribution

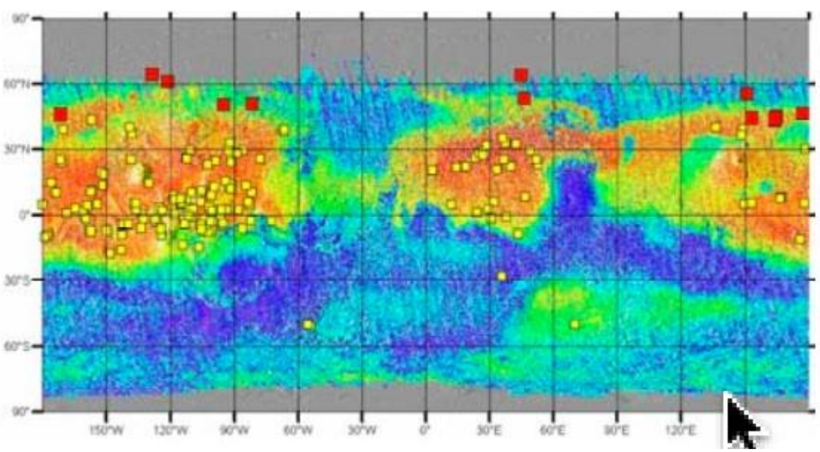
Water Abundance and Altitude with Past, Present, and Future Surface Missions



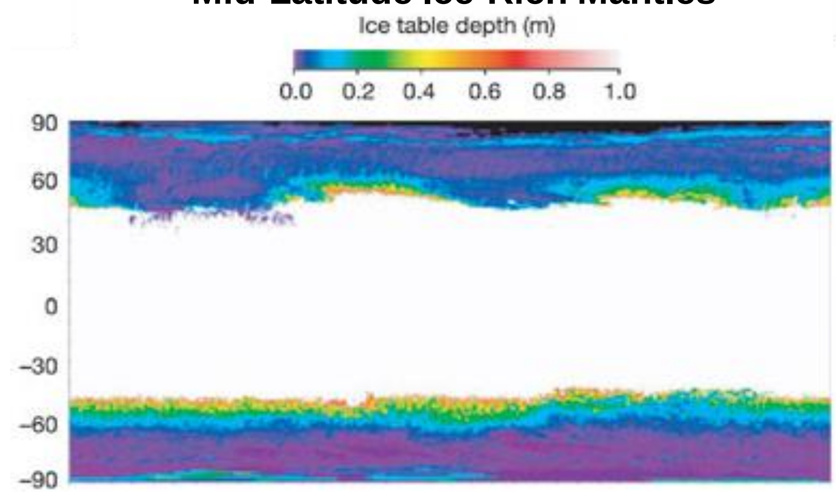
Map of aqueous mineral detections



- Minerals formed in liquid water environments
- Phyllosilicates, sulfates, carbonates contain enhanced water content, to ~8%
- Exposed in areas without mid-latitude mantle



Mid-Latitude Ice-Rich Mantles



New Craters Confirm Shallow, Nearly Pure Ice

- Newly formed craters exposing water ice (red) are a subset of all new craters (yellow). Background color is TES dust index. (Adapted from Byrne et al. (2011) Science)

Summary of What we Know About Water in "Hydrated Mineral Deposits"

Type of Deposit	General Description	How it has been Modeled Spectrally	Possible water content	Issues
Loose regolith	Powdered rock, salts, amorphous materials	Mix of plagioclase, olivine, pyroxene, npFeOx	4(2-5)% from spectral modeling and direct measurement	Easy to harvest; perchlorate salts may be common
Layered phyllosilicate	Stratified deposits rich in smectite	Mix of up to 50% smectite clays with primary igneous minerals (ol, px. Plag)	9-10% based on spectral modeling and assumed low hydration state of clays	Indurated and competent; more erodible than basalt
Crustal phyllosilicate	Smectite clays in basaltic groundmass	Mix of 5-10% smectite with weakly altered basalt	3-5% based on spectral modeling, examination by Opportunity	Fractured bedrock
Sulfate-bearing layered deposits	Dust + sand with variable content and type of sulfate cement	Mix of sulfate and hematite with Mix of plagioclase, olivine, pyroxene, npFeOx	6-14% from direct measurement of elemental abundances, hydration state from spectral models	Competent but easily erodible by wind; leaves little debris so must be fine-grained
Carbonate-bearing deposits	Olivine partly altered to carbonate	Mixture of olivine basalt and carbonate	7% based on spectral models	Probably very indurated bedrock
Hydrate silica-bearing deposits	Silica with range of hydration mixed w/ basalt	(Assumed: cement in basaltic sediment)	(5% based on assumed composition, could be up to)	Induration and purity probably highly variable

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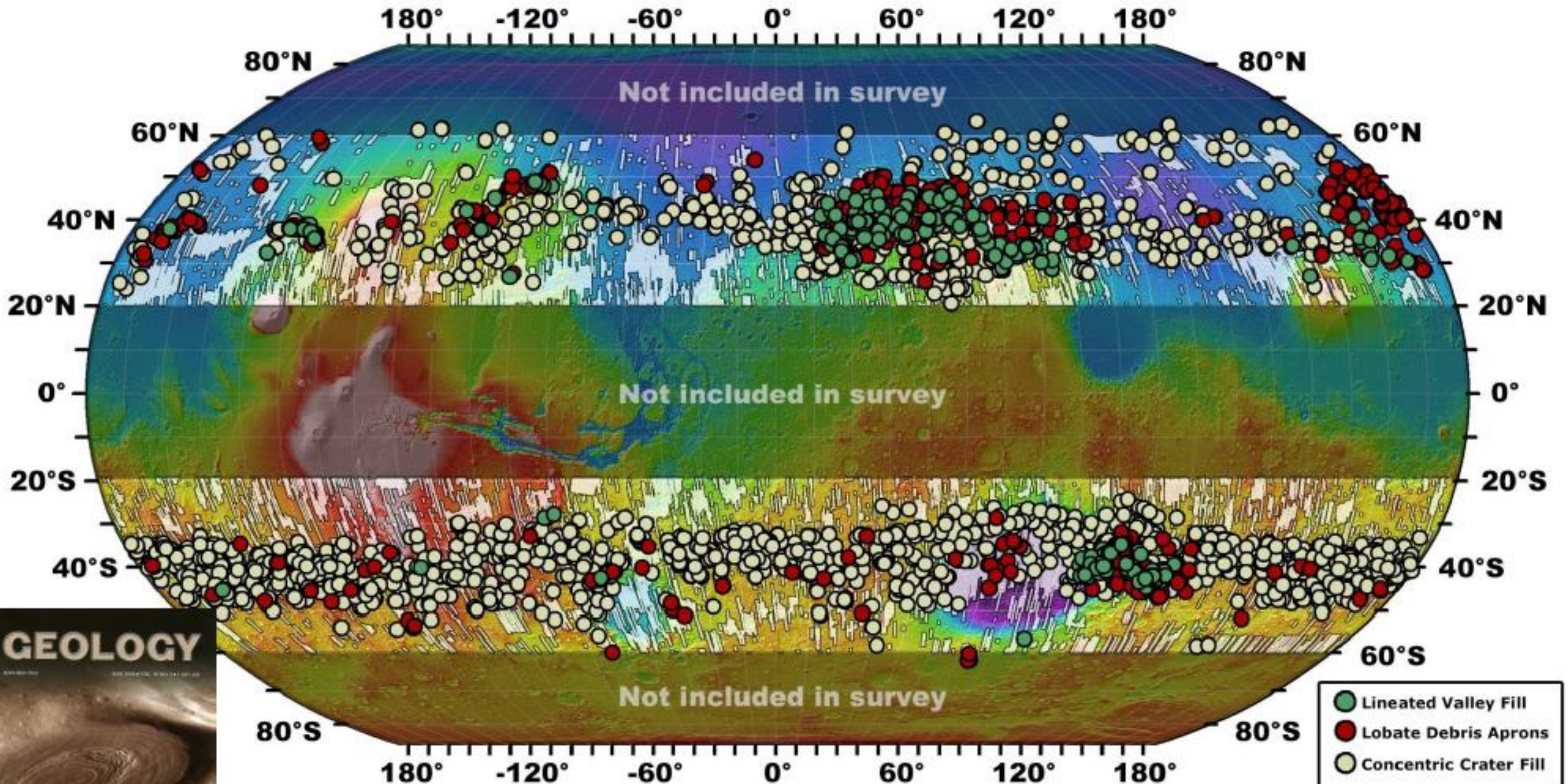
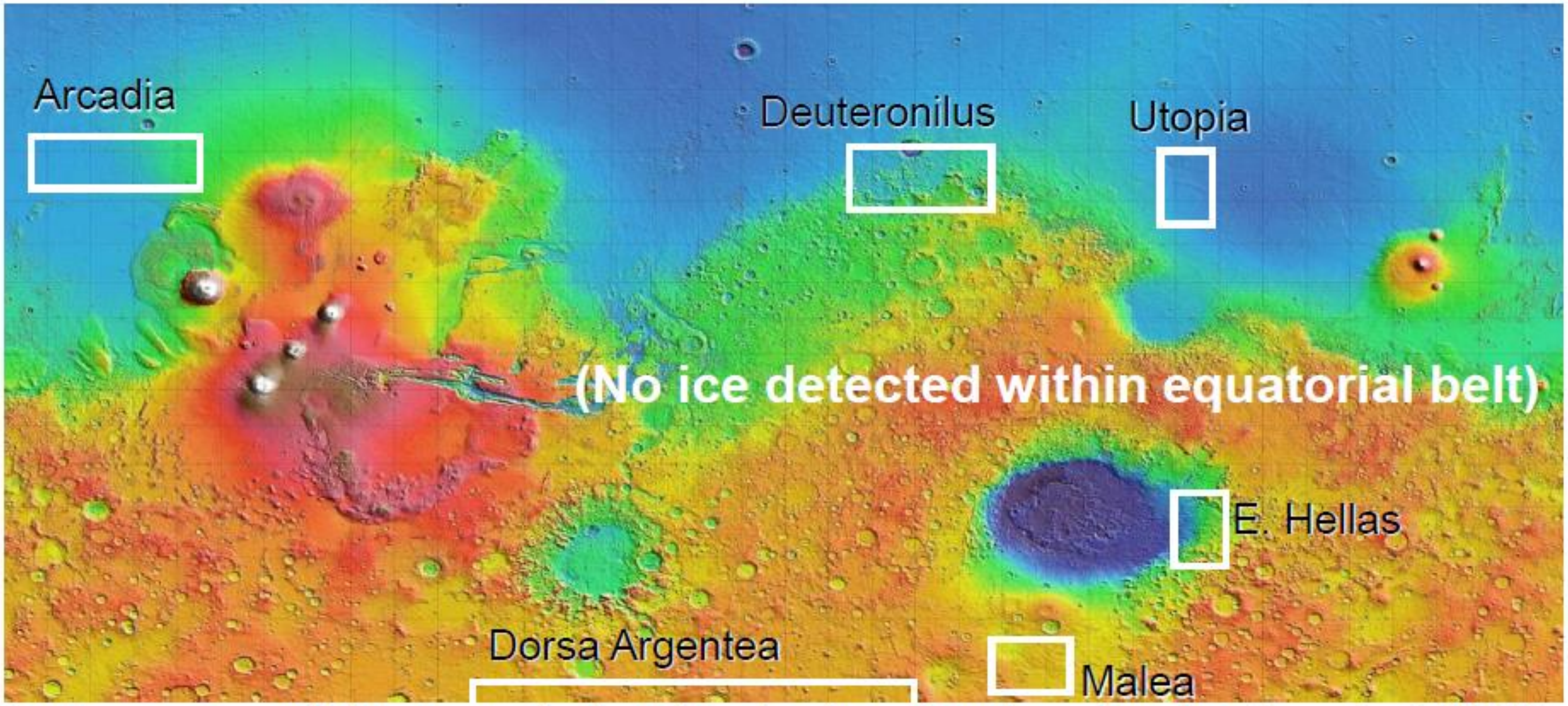
Map of Mars Glacial Features



- *With many features, <u>no information about whether residual ice remains, or at what depth</u>.*
- *Some lobate debris aprons do contain ice (next slides)*

Map from Dickson et al., 2012

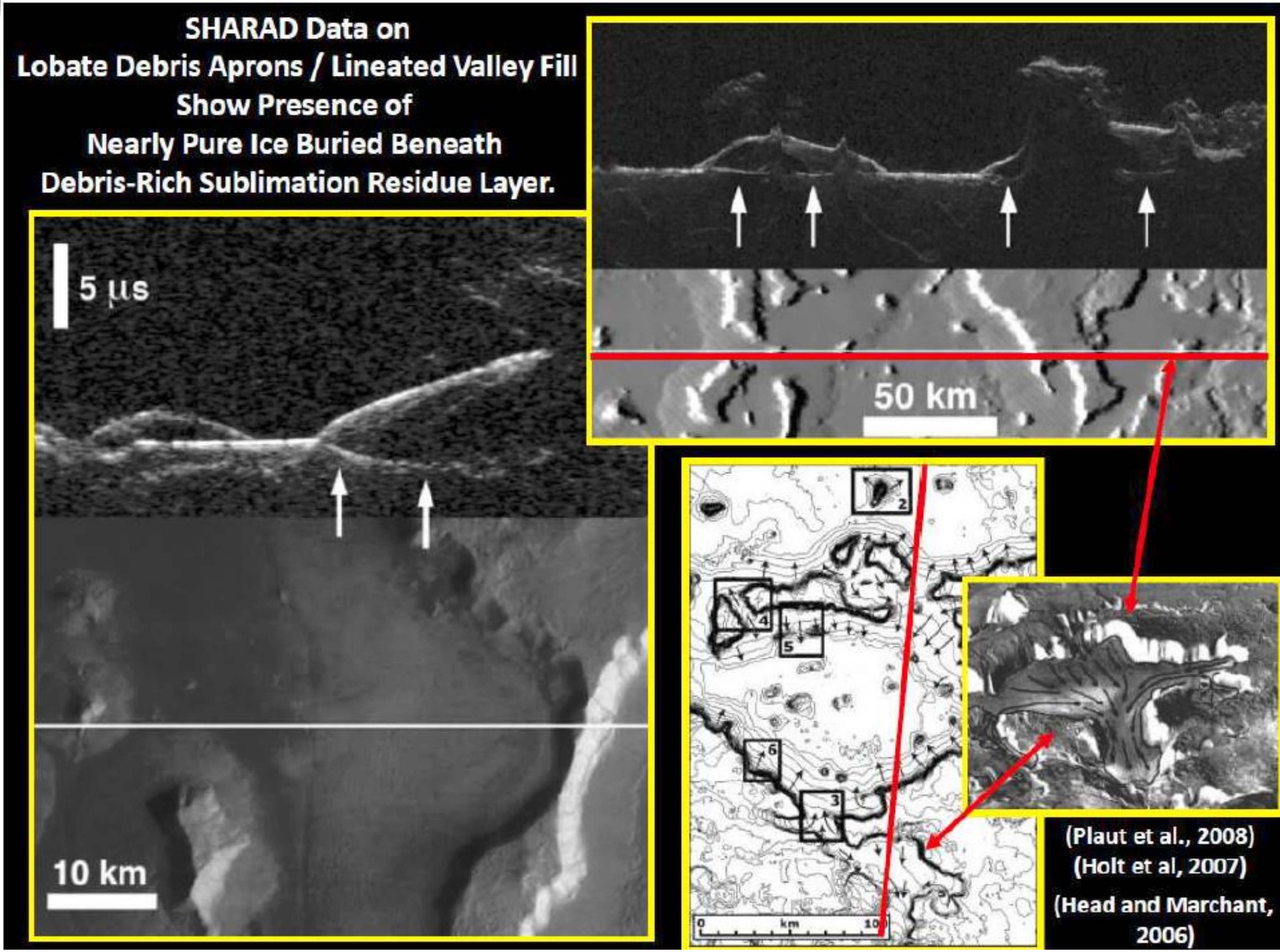
Radar Detection of Non-Polar Ice



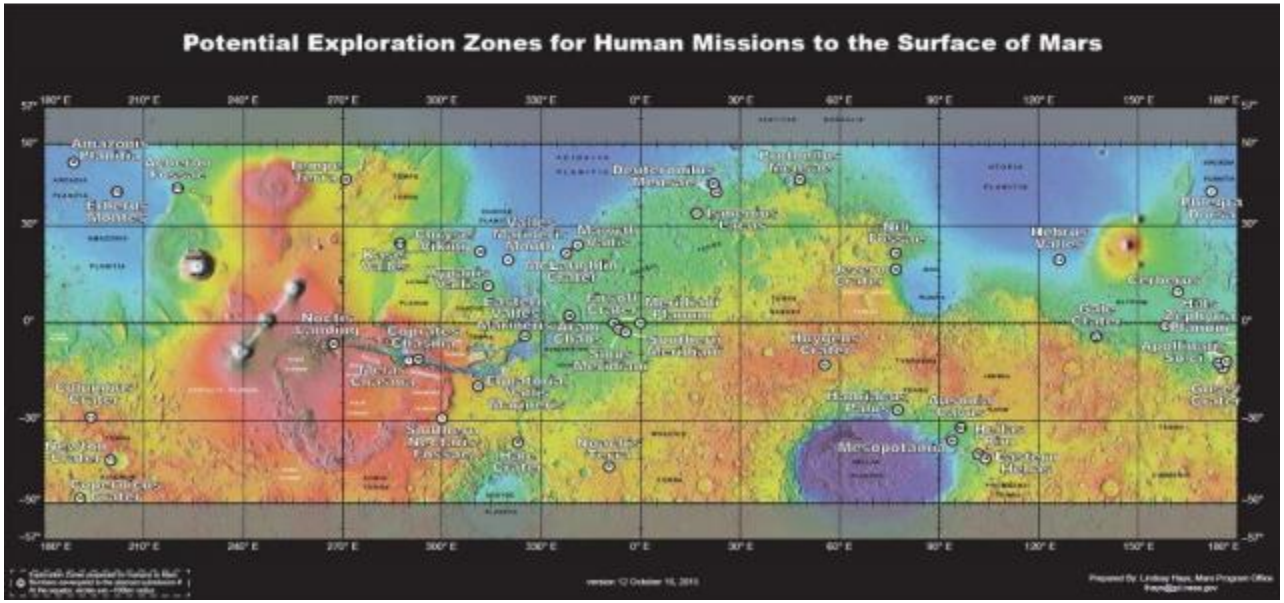
Summary map outlining areas of subsurface ice detections based on data from the MARSIS and SHARAD instruments. *Source: Special Regions SAG2, Rummel & Beaty et al., 2014.*

- Ice 100s of meters in thickness has been detected by the SHARAD radar instrument in several regions away from the poles (Plaut et al., 2009).
- Modeling estimates that these may contain 1.6 x 10^5 km^3 or ~10x North Am. Great Lakes (Karlsson et al., 2015)

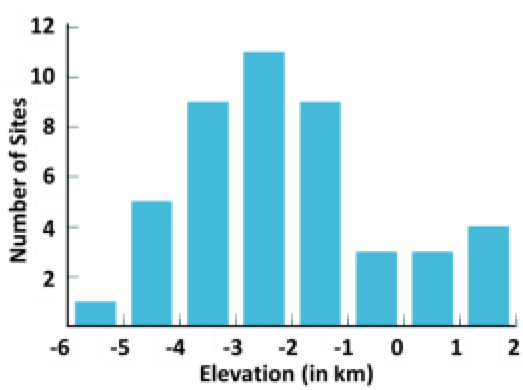
Example Radar Data for Glacier-Like Form Cross-Section NASA Internal

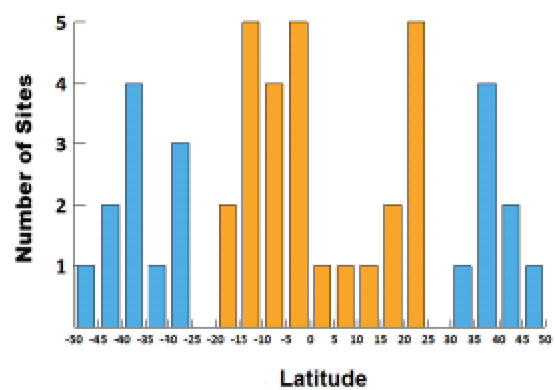


Mars Human Landing Site Workshop
(Oct. 2015 @ Lunar & Planetary Institute)



- A total of 47 EZs were proposed in 45 abstracts submitted to the Workshop





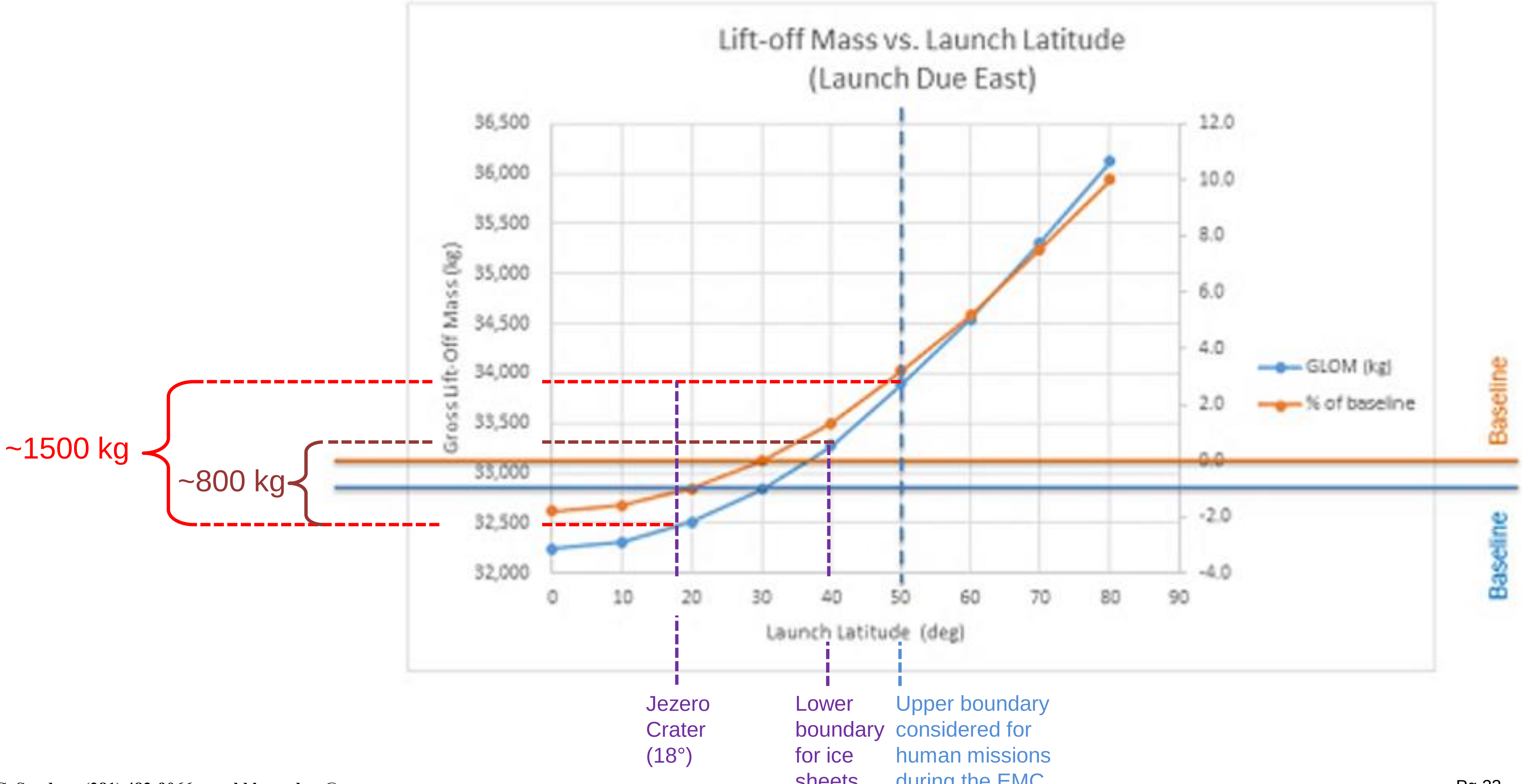
Blue represents primarily ice-based ISRU.
Orange represents primarily mineral-based ISRU.

Multiple Criteria will be used to select landing sites for human exploration of Mars

- Altitude & Latitude
  - Landing capabilities
  - Sunlight
  - Daily/year temperature
  - Atmospheric pressure
  - Dust & potential for dust storms
- Local and regional terrain
  - Landing
  - Infrastructure placement
  - Mobility
- ➢ Scientific merit
- ➢ Search for life
- ➢ Available resources, esp. water for human exploration usage

Mars Lander/Ascent Vehicle Sensitivity to Latitude

- Graph is for highlighting the sensitivity of landing latitude on Mars Ascent Vehicle (MAV) performance and mission impact on landing site selected
  - Uses data developed during the Evolvable Mars Champaign (EMC) in Fall 2015
- MAV mass increases from ~800 to ~1500 kg to go from hydrated minerals (at Jezero Crater - possible Mars 2020 landing site) to regions of potential near subsurface ice
  - Earth launch Gear Ratio equates to 6 to 16.5 mT payload increase



Challenges and Risks for ISRU

- What do we still need to know?
- What do we still need to do?

ISRU Development and Implementation Challenges/Risks

Space Resource Challenges

R1 What resources exist at the site of exploration that can be used?

R2 What are the uncertainties associated with these resources?
Form, amount, distribution, contaminants, terrain

R3 How to address planetary protection requirements?
Forward contamination/sterilization, operating in a special region, creating a special region

ISRU Technical Challenges

T1 Is it technically feasible to collect, extract, and process the resource?
Energy, Life, Performance

T2 How to achieve long duration, autonomous operation and failure recovery?
No crew, non-continuous monitoring, time delay

T3 How to achieve high reliability and minimal maintenance requirements?
Thermal cycles, mechanisms/pumps, sensors/ calibration, wear

ISRU Operation Challenges

O1 How to operate in extreme environments?
Temperature, pressure/vacuum, dust, radiation

O2 How to operate in low gravity or micro-gravity environments?
Drill/excavation force vs mass, soil/liquid motion, thermal convection/radiation

ISRU Integration Challenges

I1 How are other systems designed to incorporate ISRU products?

I2 How to optimize at the architectural level rather than the system level?

I3 How to manage the physical interfaces and interactions between ISRU and other systems?

Overcoming these challenges requires a multi-destination approach consisting of resource prospecting, process testing, and product utilization.

Location to Reduce/Eliminate ISRU Challenges/Risks

		Earth	Orbital	Surface
R1	What resources exist at the site that can be used?	S	S	**P**
R2	What are the uncertainties associated with these resources?	S	S	**P**
R3	How to address planetary protection requirements?	P		V
T1	Is it technically feasible to collect, extract, & process resources?	P		V
T2	How to achieve long duration, autonomous operation?	P		V
T3	How to achieve high reliability/minimal maintenace?	P		V
O1	How to operate in extreme environments?	S		**P**
O2	How to operate in low/micro gravity?	S		**P**
I1	How other systems designed to incorporate ISRU products?	P		V
I2	How to optimize at the architectural level with ISRU?	P		V
I3	How to manage the interfaces/interactions with other systems?	P		V

P = Primary; V = Validation, S = Support

- Most challenges and risks to ISRU development and incorporation can be eliminated through design and testing under Earth analog or environmental chamber testing at the component, subsystem, and system level
- Critical challenges/risks associated with fully understanding the extraterrestrial resource (form, concentrations, contaminants, etc.) and ISRU system operation under actual environmental conditions for extended periods of time can only be performed on the extraterrestrial surface
- ISRU precursors/demonstrations are extremely beneficial for validation of Earth-based testing and analysis

G. Sanders, (281) 483-9066, gerald.b.sanders@nasa.gov

Approach to Reduce/Eliminate Resource & Site Risks

- **Analyze Exist Data**
  - Perform analysis of orbital and surface instrument data sets to provide the most effective screening to define discrete, evaluatable, prioritized prospects

- **Improved Understanding of Soil/Water-Based Resources – What is needed?**
  - **Purpose**
    - Determine resource availability, geologic context, depth, distribution, and homogeneity, and applicability to other locations on Mars
    - To support mining operations and infrastructure emplacement (terrain, environment, wind, sun)
  - **Sequence of knowledge/analyses needed**
    - Global understanding of resources/terrain to select landing sites
    - Higher resolution data for regions of interest (ROI) for landing
    - 1 meter or less resolution of terrain and <100 m resolution of resources in locations within ROI for landing site selection and preliminary infrastructure layout plans
    - <5 m resolution of resources to select mining sites of interest
    - <1 m mapping of terrain, surface/subsurface features and resources with ground truth verification of resources (and contaminants) at statistically relevant intervals to plan and perform mining operations and finalize mining hardware designs

Orbital/ Aerial

Aerial/ Surface

  - **Different ISRU phasing strategies can influence scope and timing of resource assessment**
    - Strategy 1: Start with lowest risk resource (hydrated mineral at surface) near initial infrastructure before or during 1st crewed mission. Perform resource evaluation and ISRU risk reduction demos on larger quantity/higher concentration resources as time goes on with crew present
    - Strategy 2: Identify the resource type of primary interest. Locate and perform ISRU risk reduction demos on that resource before crew arrives

G. Sanders, (281) 483-9066, gerald.b.sanders@nasa.gov

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  - **Sequence of knowledge/analyses needed**

Current Knowledge

    - Global understanding of resources/terrain to select landing sites
    - Higher resolution data for regions of interest (ROI) for landing
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    - <5 m resolution of resources to select mining sites of interest
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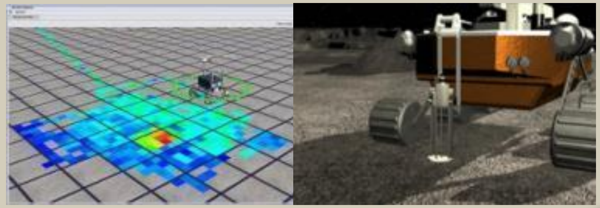
Prospecting Is Needed Before Usage is Possible

Resource Assessment (Prospecting and Feasibility)

Global Resource Identification

Local Resource Exploration/Planning



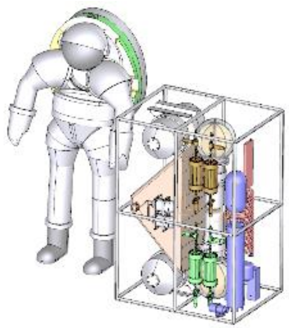
Mining

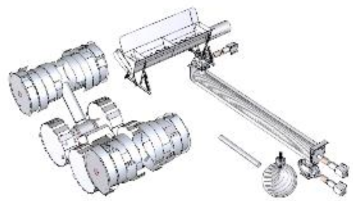
Terrestrial Approach

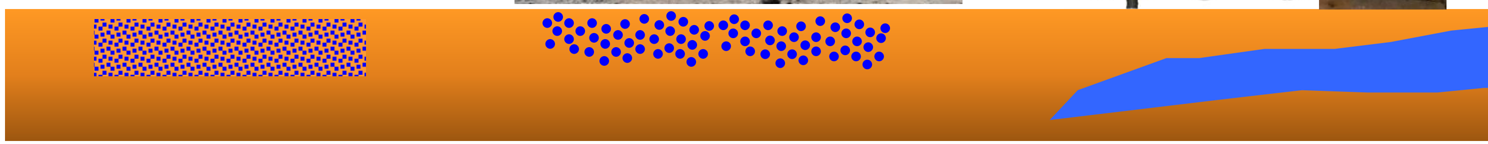
Concepts of Operation for Water-based ISRU on Mars

Mars Atmosphere & Water Resource Attributes

Atmosphere Processing	Granular Regolith Processing for Water	Gypsum/Sulfate Processing for Water	Icy Regolith Processing for Water







Atmosphere
- Pressure: 6 to 10 torr (~0.08 to 0.1 psi);
- >95% Carbon Dioxide
- Atm. temperature: +35 C to -125 C
- **Everywhere on Mars;** Lower altitude the better
- Chemical processing similar to life support and regenerative power

Mars Garden Variety Soil
- **Low water concentration 1-3%**
- **At surface**
- **Granular;** Easy to excavate
- **300 to 400 C heating for water removal**
- Excavate and transfer to centralized soil processing plant
- **Most places on Mars**; 0 to +50 Deg. latitude

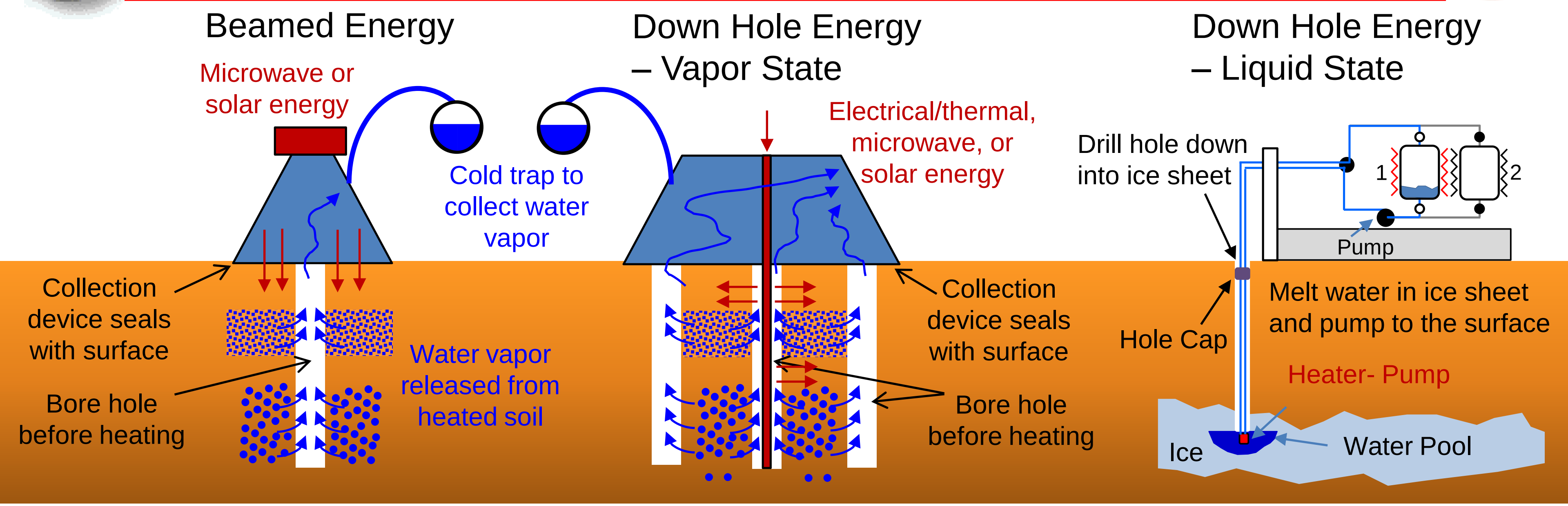
Gypsum or Sulfates
- Hydrated minerals 5-10%
- **At Surface**
- **Harder material:** rock excavation and crushing may be required
- **150 to 250 C heating for water removal**
- **Localized concentration in equatorial and mid latitudes**

Subsurface Ice
- **90%+ concentration**
- **Subsurface glacier or crater**: 1 to 3 m from surface possible
- **Hard material**
- **100 to 150 C heating for water removal**
- Downhole or on-rover processing for water removal
- **Highly selective landing site for near surface ice or exposed crater;** >40 to +55 Deg. latitude

Increasing Complexity, Difficulty, and Site Specificity

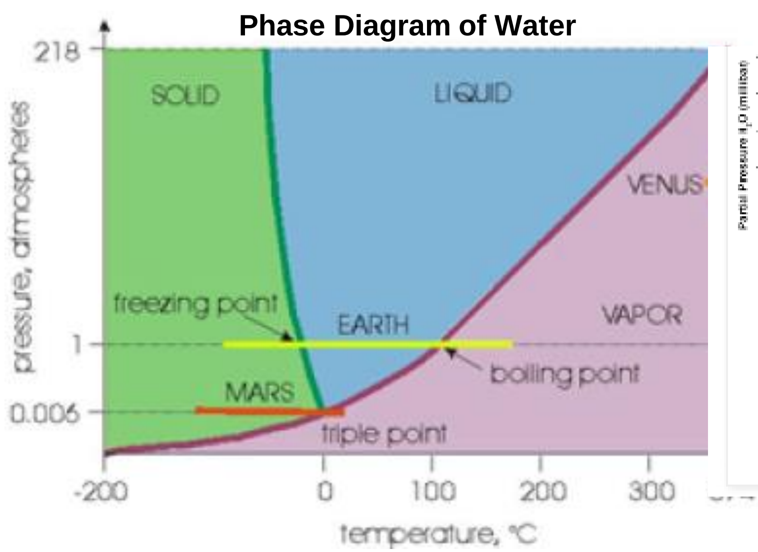
G. Sanders, (281) 483-9066, gerald.b.sanders@nasa.gov

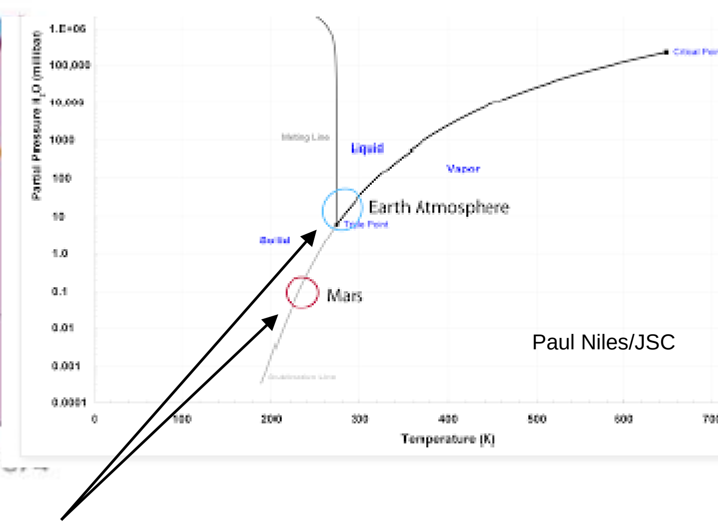
In Situ Water Extraction from Mars Soils



- Energy heats soil so that water converts to vapor (may transition thru liquid phase)
- Release of water helps further heat conduction into soil
- Water vapor follows 'path of least resistance' to bore hole
  - Vapor may also re-condense away from heat in colder soil
- Water vapor collected in cold trap in liquid/solid form
- Process may take hours

Phase Diagram of Water

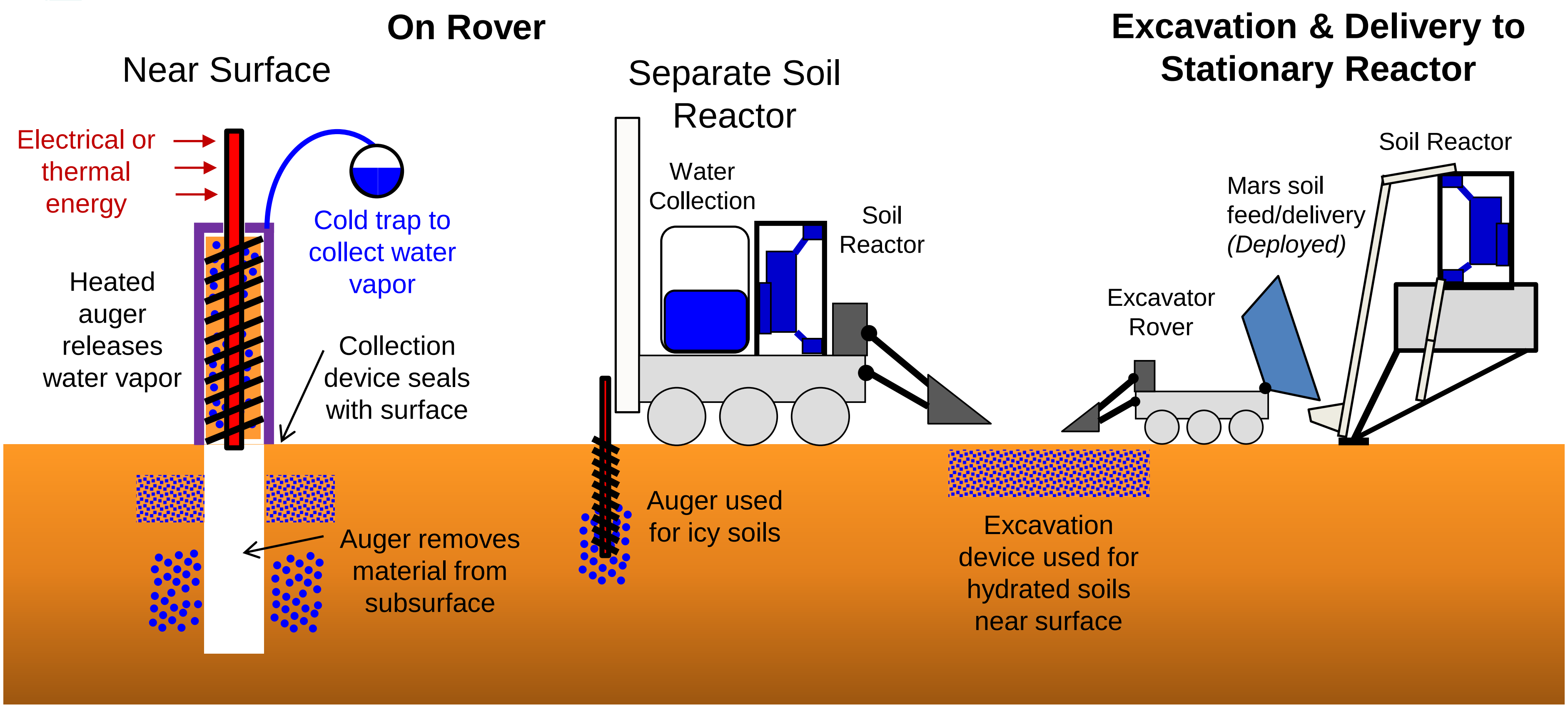




When we are dealing with an atmosphere, we should instead use the "partial pressure" of water vapor in the atmosphere to calculate the stability of water.

G. Sanders, (281) 483-9066, gerald.b.sanders@nasa.gov

Water Extraction via Excavation & Processing Reactor



- Soil is removed from subsurface
- Soil is heated via thermal to remove water vapor; can be higher temperature than *in situ* heating

- Soil is removed from surface/subsurface and transferred to soil reactor
- Soil is heated via thermal, microwave, and/or gas convection to remove water vapor at higher temperatures and pressures than for *in situ* heating

- Water vapor is condensed and stored
- Soil is dumped back onto surface after processing

Mars ISRU ConOps Trade Tree

Choices Made Impact Technologies and Operations

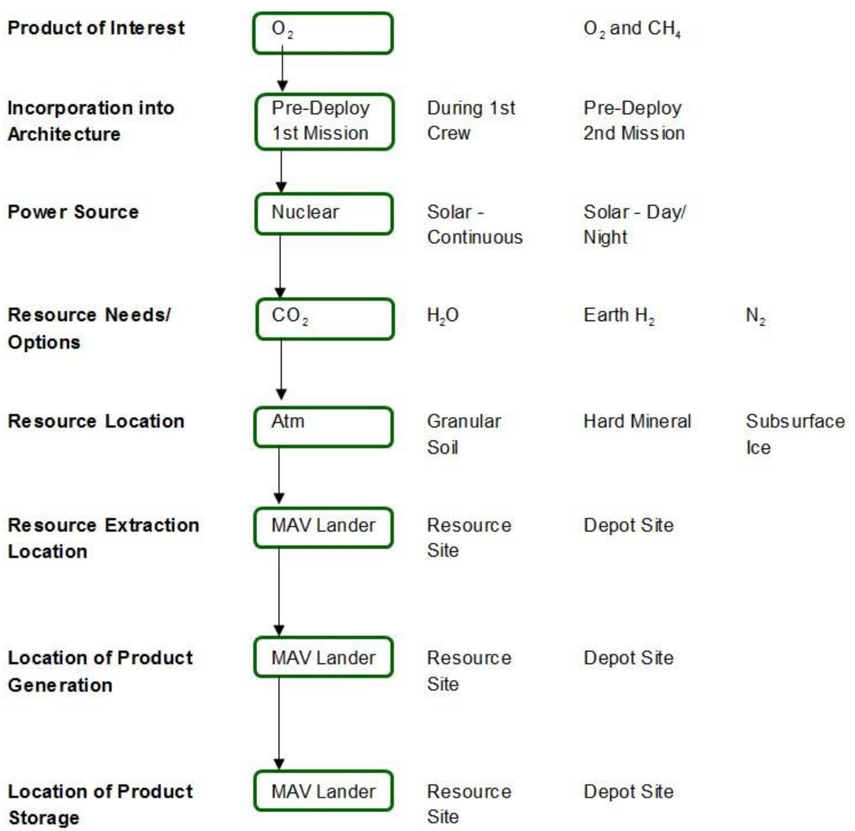
Product of Interest	O_2		O_2 and CH_4	
Incorporation into Architecture	Pre-Deploy 1st Mission	During 1st Crew	Pre-Deploy 2nd Mission	
Power Source	Nuclear	Solar - Continuous	Solar - Day/ Night	
Resource Needs/ Options	CO_2	H_2O	Earth H_2	N_2
Resource Location	Atm	Granular Soil	Hard Mineral	Subsurface Ice
Resource Extraction Location	MAV Lander	Resource Site	Depot Site	
Location of Product Generation	MAV Lander	Resource Site	Depot Site	
Location of Product Storage	MAV Lander	Resource Site	Depot Site	
Post MAV Fill?	**Maintain MAV**	**Fill Lander 3**	**Fill Depot**	

This is where the resource is extracted from bulk material (i.e water from soil & CO_2 from atm.)

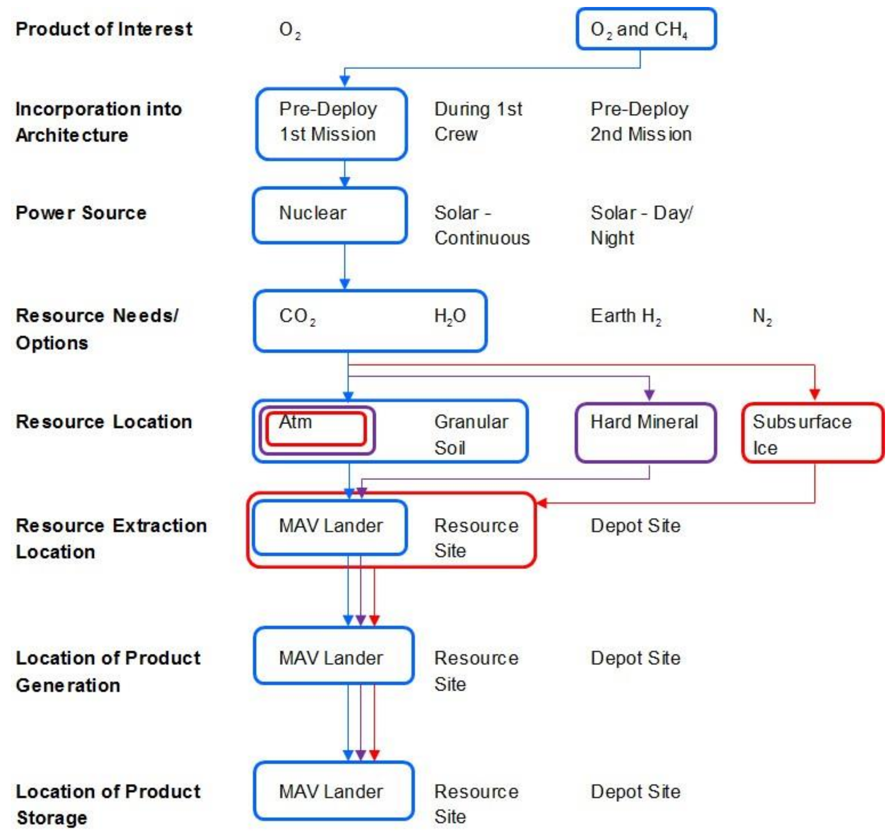
This is where the resource is converted into the desired product

Mars ISRU Concepts of Operation

Baseline: O_2 Only Production from Mars Atmosphere CO_2



Option: O_2/CH4 Production from Mars Atmosphere CO_2 and Soil H_2O



G. Sanders, (281) 483-9066, gerald.b.sanders@nasa.gov

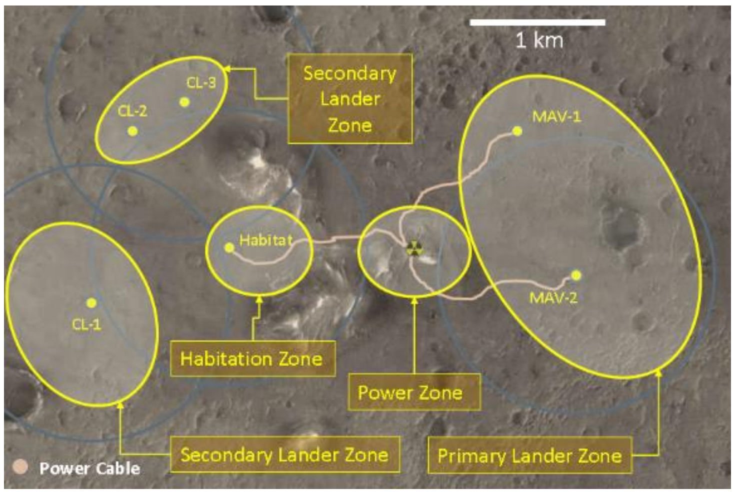
ISRU Products, Operations, and Resources Grow As Mission Needs and Infrastructure Grow

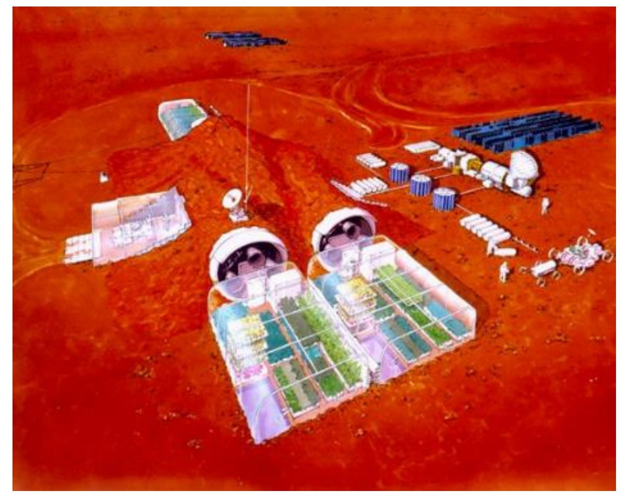
Initial Conditions:

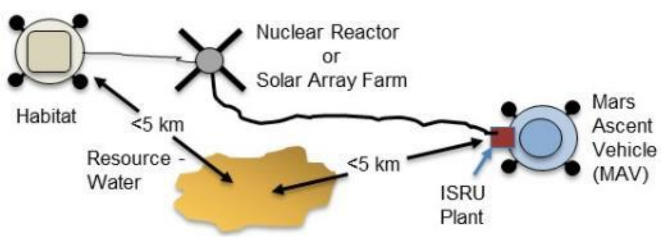
- Hardware delivered by multiple landers before crew arrives; Multiple landing zones
- Elements offloaded, moved, deployed, and connected together remotely
- 12-18 month stay for crew of 4 to 6; Gaps of time between missions where crew is not present
- Each mission delivers extra hardware & logistics

Ultimate Goal

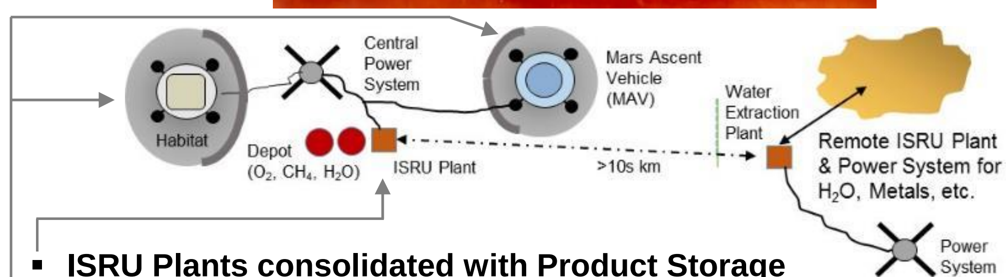
- Consolidated and integrated infrastructure
- Indefinite stay with larger crews
- Roam (and mine) anywhere within 200 km diameter Exploration Zone
- Earth independence; *In situ* ability to grow infrastructure: power, habitation, food, parts, etc.







- **ISRU hardware integrated with Landers**
- **'Easy' Resource very close to landing site/ Ascent vehicle**

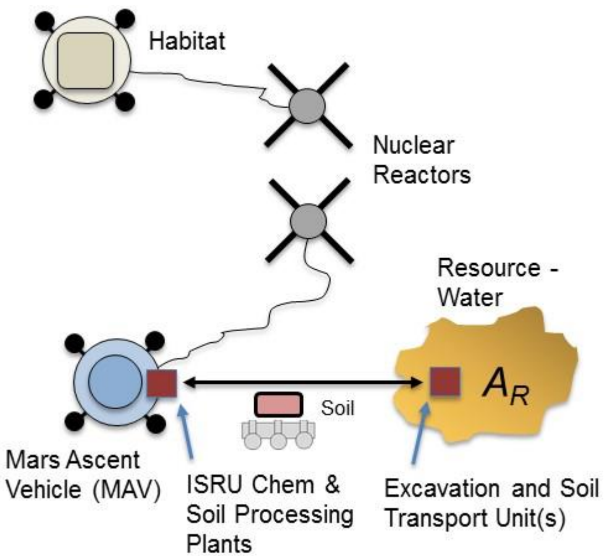


- **ISRU Plants consolidated with Product Storage**
- **Civil Engineering and *In Situ* Construction operations**
- **Resources can now be farther from Habitat and Ascent Vehicle**
- **More/different resources needed for Earth independence**

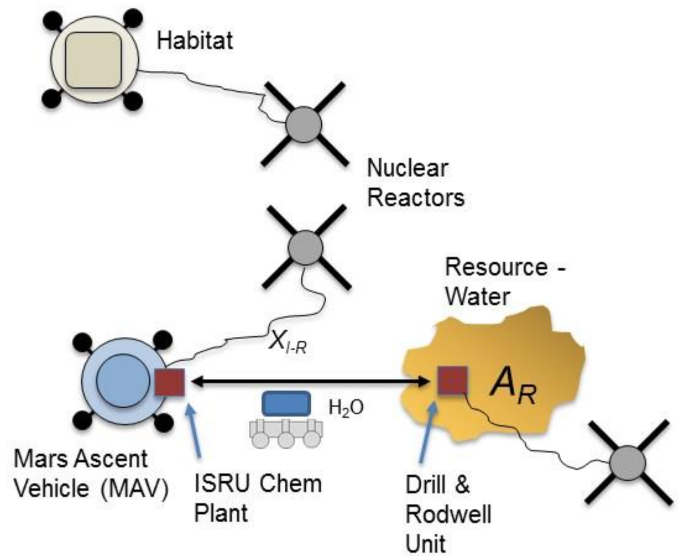
How Will Water be Mined on Mars?

Approach Selected will depend on:

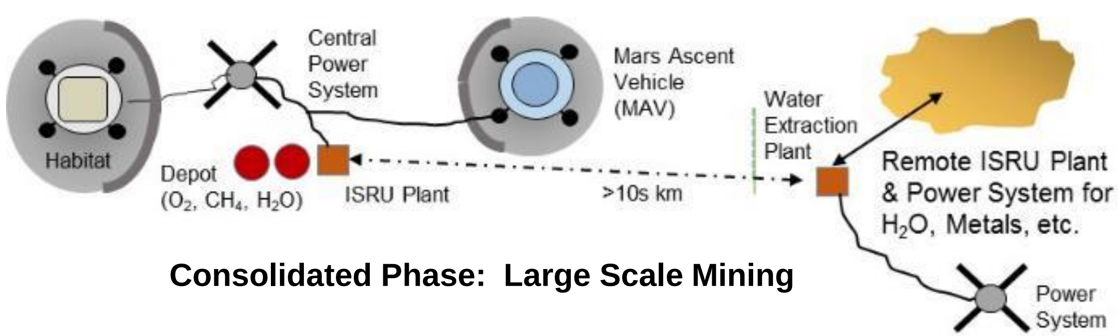
- Concentration of water resource
- Distance from ISRU and human support infrastructure
- Phase of human exploration of the Mars surface



Initial Phase: Low concentration Near ISRU/MAV



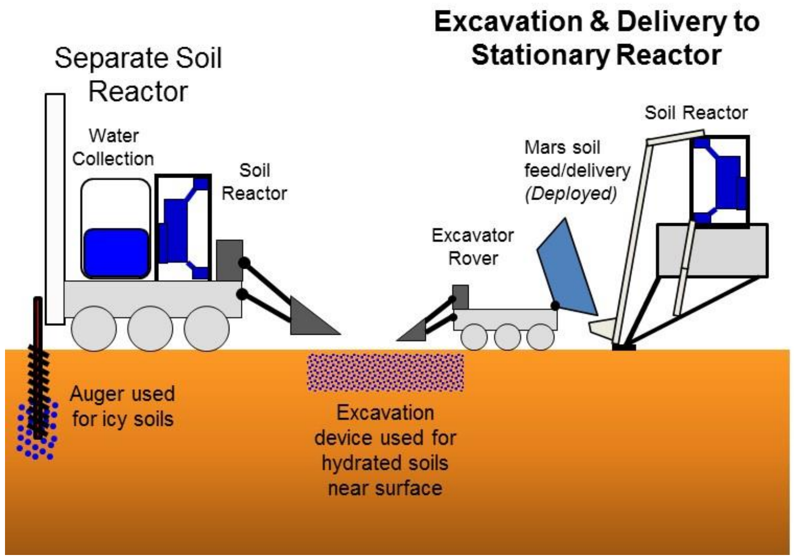
Initial Phase: High concentration Near ISRU/MAV



Consolidated Phase: Large Scale Mining

G. Sanders, (281) 483-9066, gerald.b.sanders@nasa.gov

Mars Hydrated Water Mining Process Options & Hardware



Soil Acquisition and Excavation

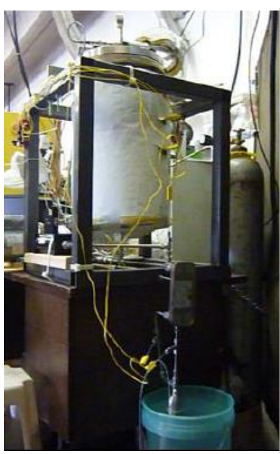
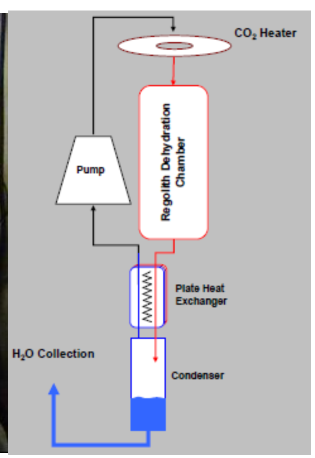
- Sample drills and augers (JPL, ARC, SBIRs)
- Scoops and buckets (GRC, KSC, JPL, Univ., SBIRs)
- Auger and pneumatic transfer (KSC, GRC, SBIRs)



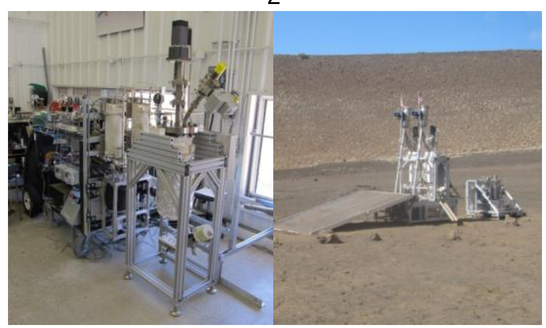



Lunar/Mars Soil Processing

Pioneer Astronautics Hot CO_2 Water Extraction from Soil

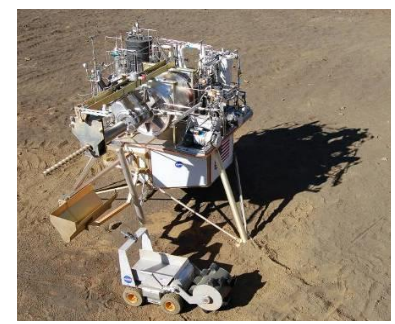



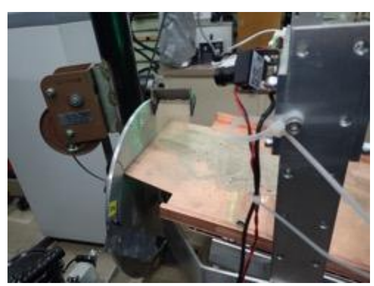
1[st] Gen H_2 Reduction from Regolith Systems (NASA, LMA)



ROxygen H_2 Reduction
Water Electrolysis
Cratos Excavator

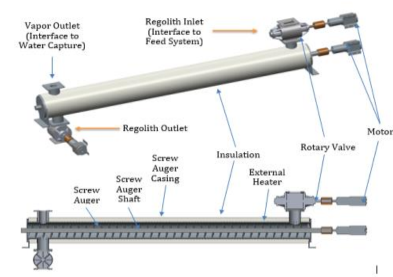
PILOT H_2 Reduction
Water Electrolysis
Bucketdrum Excavator





Concept for 'open-air' water extraction soil processor

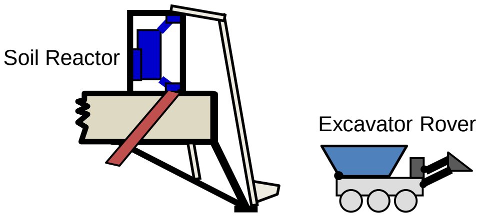
Screw-conveyor dryer soil processor concept



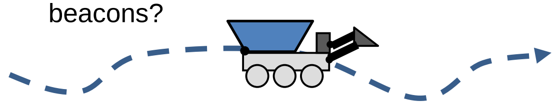
G. Sanders, (281) 483-9066, gerald.b.sanders@nasa.gov

Granular Hydrated Material Mining Operations

1. Rover/Excavator Deploys from Lander
   - Unload rover
   - Activate rover

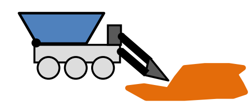


2. Excavator Rover Traverses to Excavation Site
   - Use route planned from Earth based on terrain/location map
   - Avoid obstacles and potentially other rovers during traverse
   - Autonomous operation; Use trail of beacons?

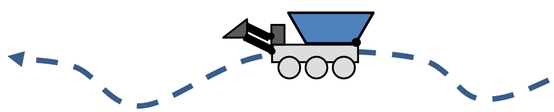


3. Excavator Rover Arrives at Excavation Site
   - Survey location to determine difference since last excavation to select excavation site (on-rover or LIDAR at site?)
   - Rover traverses to selected site

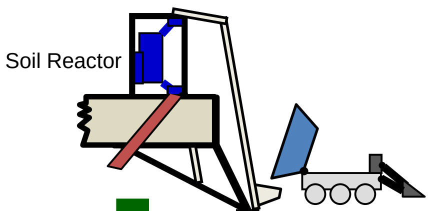
4. Excavator Rover Performs Excavation
   - Line up excavation device to exact point for excavation
   - Perform excavation; monitor forces on excavation device and wheel slippage to ensure proper excavation
   - Measure amount of soil excavated and loaded onto the rover



5. Excavator Rover Traverses back to Soil Processor
   - Use route planned from Earth based on terrain/location map
   - Avoid obstacles and potentially other rovers during traverse
   - Autonomous operation; Use trail of beacons?

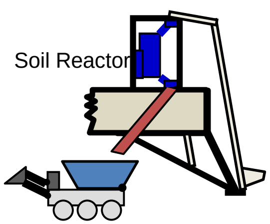


6. Excavator Rover Delivers Soil to Processor
   - Rover finds dumping soil bin
   - Rover lines up to dump soil
   - Rover dumps soil. Measure mass change to ensure soil has been delivered?

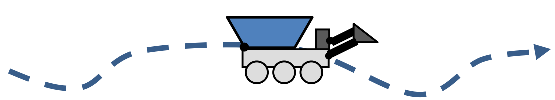


7a. Recharge Rover (if needed)
   - Rover finds charging port
   - Rover docks to charging port

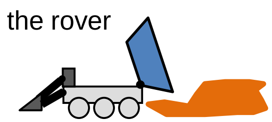
7b. Excavator Rover Receives Processed Soil
   - Rover finds dumping soil bin
   - Rover lines up to dump soil
   - Rover receives spent soil. Measure mass?



8. Excavator Rover Traverses to Dump Location
   - Use route planned from Earth based on terrain/location map
   - Avoid obstacles and potentially other rovers during traverse
   - Autonomous operation; Use trail of beacons?



9. Excavator Rover Arrives at Dump Site
   - Survey location to determine difference since last dump to select dump site
   - Rover traverses to selected site
   - Line up dump device to exact point for dumping
   - Perform dumping
   - Measure amount of soil dumped from the rover

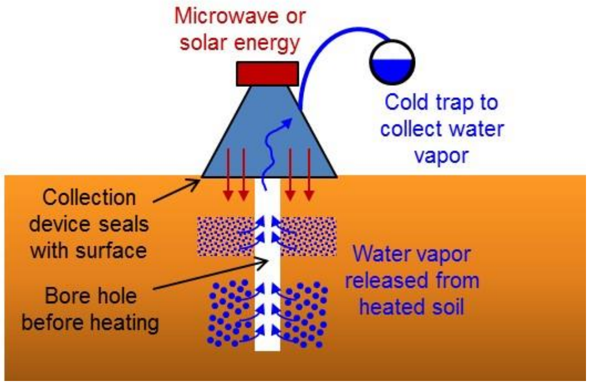


Return to Step 2

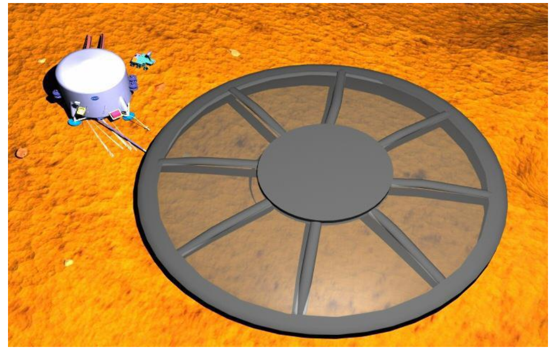
G. Sanders, (281) 483-9066, gerald.b.sanders@nasa.gov

Mars Ice Mining Process Options & Hardware (1)

Beamed Energy

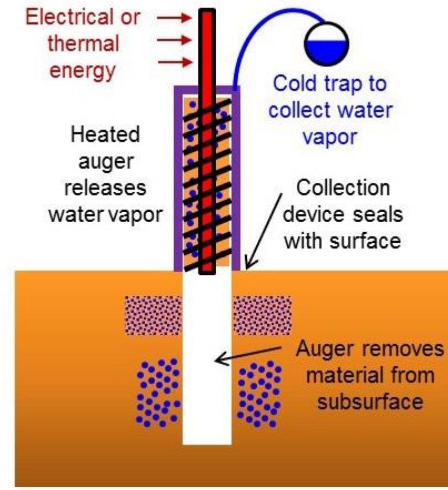


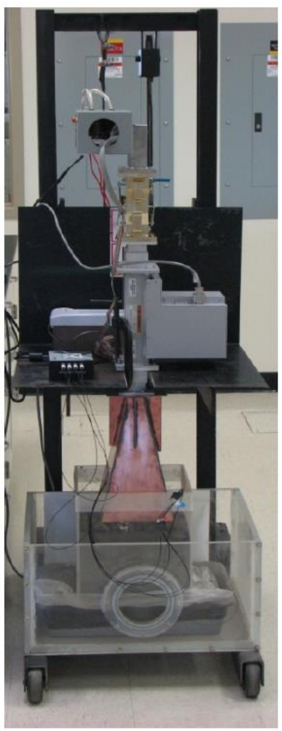
Solar Heating & Collection



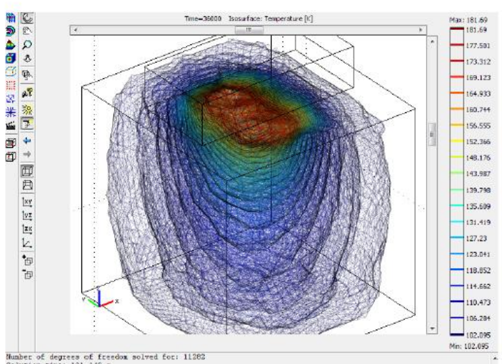
No or limited technical work

On Rover

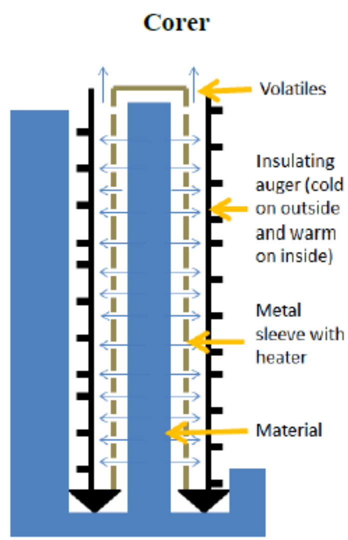


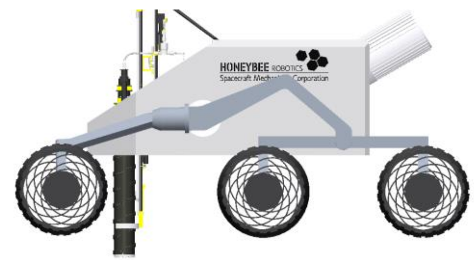


AIAA 2011-612, "**Microwave Processing of Planetary Surfaces for the Extraction of Volatiles**", Edwin C. Ethridge1



Honeybee Corer Concept (Near-Surface Ice)





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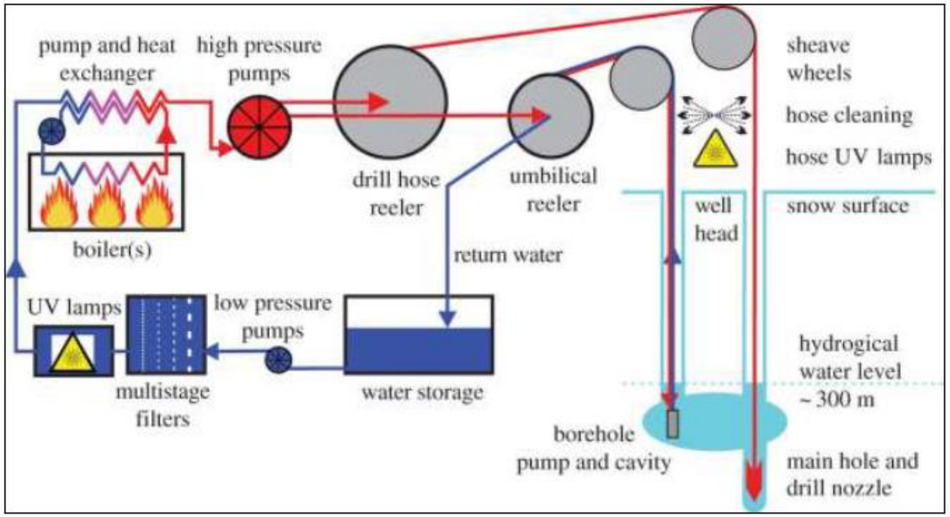
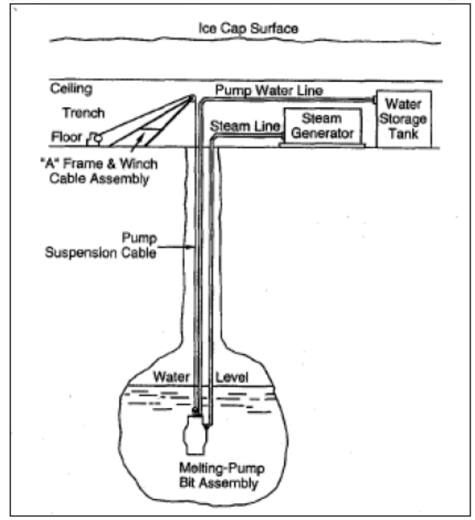
Mars Ice Mining Process Options & Hardware (2)

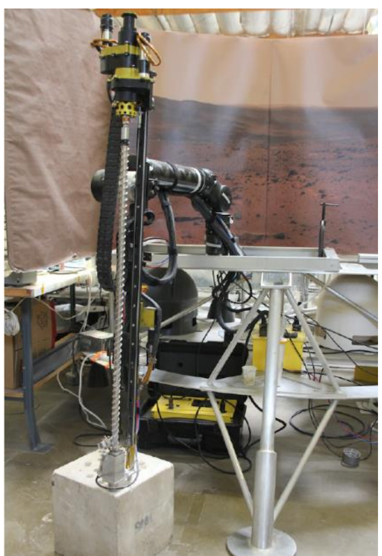
Rodwell Concept (Deep Ice)





- Drilling Options
  - Mechanical drill
  - Electrothermal drill
  - Hot water drill
- Subsurface Ice Heating Options
  - Hot water pumped from surface
    - Thermal energy from Nuclear reactor
    - Electrical
  - Electric Heater

Honeybee Robotics Icebreaker 2m Drill



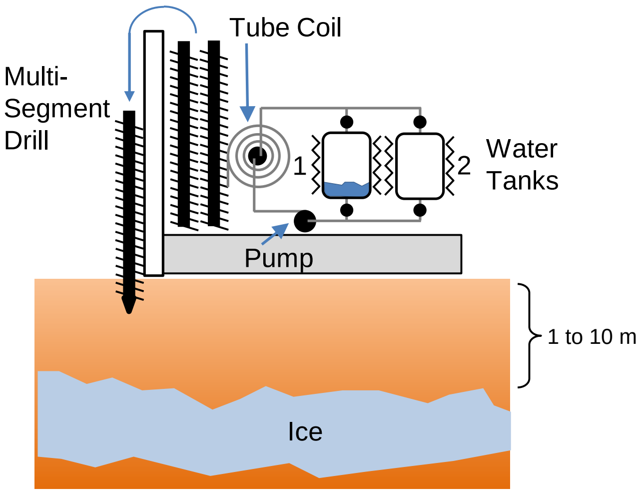
Mars Analog Research & Technology Experiment (MARTE) 10m Drill

NASA RASC-AL Mars Ice Challenge 2017

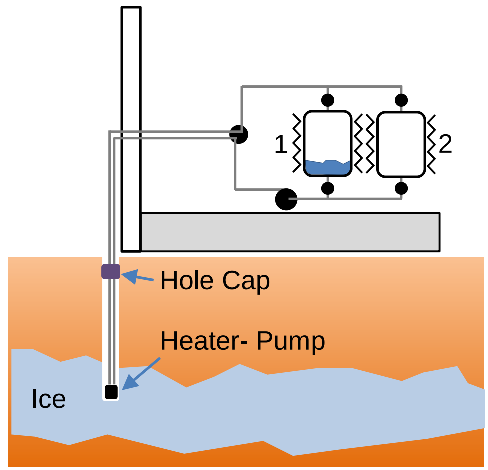
Terrestrial Experience

Subsurface Ice Mining Operations

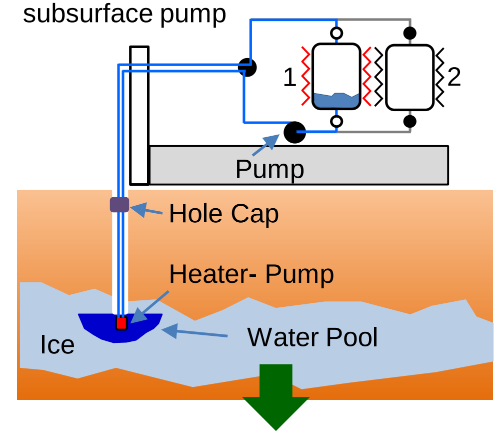
1. Drill through overburden into ice
   - Multi-segment drill from 1 to 10 m
   - Measure while drilling to evaluate when ice is met
   - Examine drill tailings or sensor on drill head for ice detection



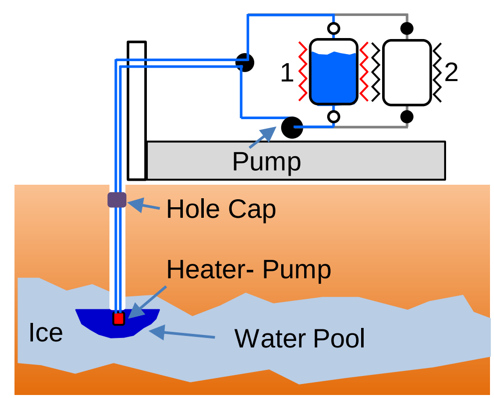
2. Establish tubing for water extraction
   - Lower tube with internal tubes for water flow down and up from Rodwell
   - End of tube includes downhole heater and water pump
   - Cap tube hole and tube (pneumatic) to seal chamber.



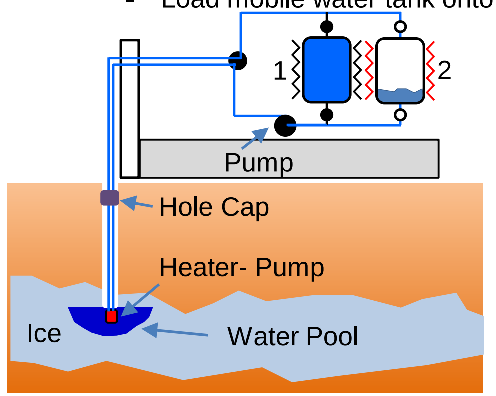
3. Begin water extraction from subsurface ice
   - Heat subsurface ice with downhole heater to begin subsurface water pool
   - Heat water from attached mobile water tank (precharged with amount to start ops) electrically or with thermal energy from FSPS
   - Begin flow of water from surface to subsurface to charge line with surface pump
   - Begin subsurface water extraction with subsurface pump



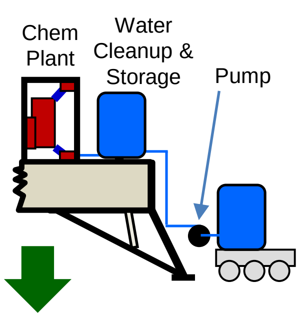
4. Continued water extraction
   - Continue extraction of water from subsurface pool into mobile water tank at balanced rate until



5. Remove mobile water tank for delivery
   - Attach and warm 2nd mobile water tank
   - Divert flow to 2nd mobile water tank
   - Detach 1st mobile water tank
   - Load mobile water tank onto Asset 1 or 2



6. Deliver Mobile Water tank to ISRU Chem Plant
   - Rover finds attachment point for water transfer
   - Rover lines up and connects mobile water tank
   - Transfer water to on-board water cleanup and storage tank



7. Return Mobile Water tank to Rodwell Unit

G. Sanders, (281) 483-9066, gerald.b.sanders@nasa.gov

Mars Water ISRU and Connection to Planetary Protection/Search for Life

Updated from Presentation Given at the
Workshop on
Planetary Protection Knowledge Gaps for Human Extraterrestrial Missions
Mar 24-26, 2015 @ NASA ARC

ISRU Water Prospecting and Science

- **Both science and ISRU want to better understand the form and distribution of water on Mars and the geological context in which it is found**
  - ISRU wants understanding over 100's of meters to kilometers around potential human landing sites
- **Both ISRU and the Search for Life want to "Follow the Water"**
- **Some combination of capabilities and instruments from missions below is highly desirable**

Mission	Terrain	Physical	Mineral	Volatile	Environment
Mars Exploration Rovers	Panoramic Camera	Microscopic Imager Rock abrasion tool	Panoramic Camera Alpha Proton X-ray Spec Mossbauer Spectrometer Miniature Thermal Emission Spectrometer		
Mars Curiosity Rover	Mast Camera	Mars Hand Lens Imager	Alpha Proton X-ray Spec	SAM Gas Chromatograph/ Mass Spectometer; TDL	Environment Monitoring Station
		Sample Drill (cm)	Laser Induced Breakdown Spectroscopy (LIBS) X-Ray Diffraction/X-Ray Fluorescence	Neutron Spectrometer w Pulsing Neutron Gen.	Radiation Detector
ExoMars	Mast Camera	Ground Penetrating Radar	Micro infrared imaging spectrometer	GC-MS and Laser Desorption Ion Source	
		Sample Drill (2 or 3 m)	Raman Spectrometer X-Ray Diffraction Mossbauer Spectrometer Infrared Spectrometer		
Resource Prospector RESOLVE	Mast Camera	Sample Drill (1 m)	Near Infrared Spectrometer	GC-MS Near IR Neutron Spectrometer	
RLEP 2 (Proposed)	Mast Camera	Sample Drill (2) Arm/scoop Cone penetrometer/shear vane		Neutron spectrometer Ground Penetrating Radar GC-MS with TDL	

Planetary Protection Concerns for ISRU and Search for Life

- **Forward contamination: Biological traces introduced to Mars**
- **Creation of special region: liquid water at 'comfortable' temperatures for long periods of time**
  - COSPAR defines Special Regions as "a region within which terrestrial organisms are likely to replicate"

Further Concerns for ISRU and Crewed Operations

- **Release of solids (dust grains) generated by excavation or drilling or reactor feeding spillover etc… after contact with machinery may be transported by winds and deposited somewhere else.**
- **Subsurface material attaches to spacesuit and goes into habitat through maintenance activities**
- **Release of gases/liquids through leakage, venting operations, or failure that could confuse search for life**

➢ **Note: ISRU processes considered for this presentation do not include biological or synthetic biology approaches**

Water on Mars Summary

- **Water can be found on Mars from very low concentrations (<2% by mass) at the equator to very high concentrations (dirty ice) at the poles**

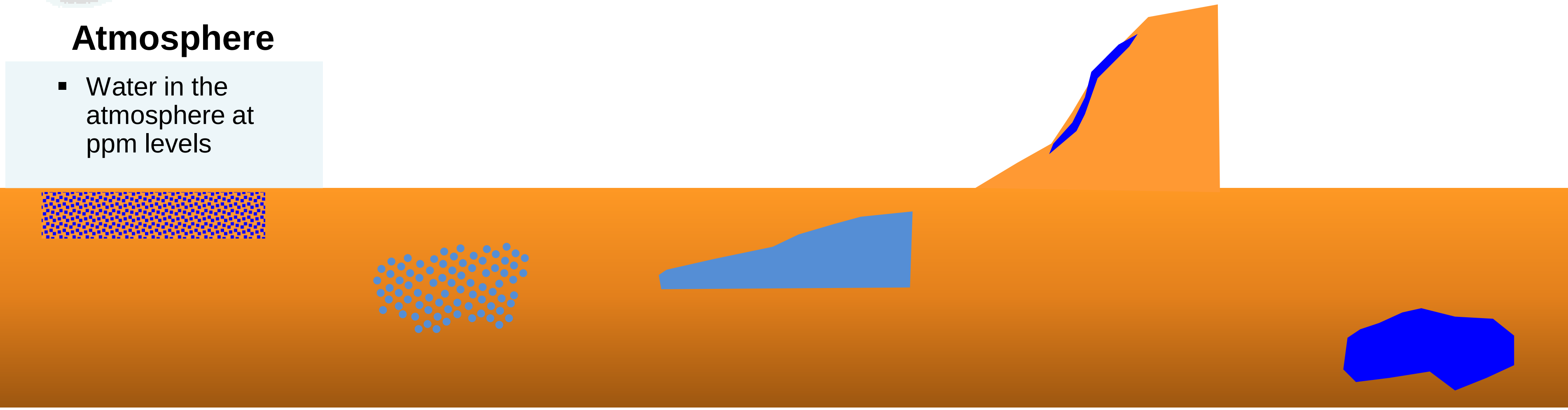
- **Water may be found in several forms based on the location on Mars**
  1. Water of hydration in minerals (<2 to ~13% by mass) – primary at equator and lower latitudes
  2. Subsurface ice/permafrost within the top 5 meters in the mid latitudes
  3. Shallow, nearly pure ice in newly formed craters in mid-upper latitudes
  4. Dirty ice at polar locations
  5. Recurring slope lineae (RSL) may be water??? Located at equator-facing sunward-facing sides of craters/ridges in the 30° to 50° latitude range
  6. Subterranean aquifers???
  - Note:
    a. Forms 1 & 2 are the most likely resource based on potential landing locations
    b. Forms 5 & 6 are most likely not of interest for ISRU due to access difficulty (5) and planetary protection (6)

- **Most of the water in the soil can be removed by heating to <450°C**
  - >80% of the water released
  - CO_2 and O_2 released from decomposition of perchlorates (est. to be <0.8% by mass)
  - Some release of HCl or H_2S but before significant amounts are release at higher temperatures

Water on Mars
(Simplified)

Atmosphere

- Water in the atmosphere at ppm levels



Hydrated Soil

- Water of hydration in minerals
- <2 to ~13% by mass
- Primary at equator and lower latitudes
- At/near surface

Permafrost & Icy Soils

- Icy soils and permafrost within the top 5 meters in the mid latitudes

Subsurface Ice

- Shallow, nearly pure ice in mid-upper latitudes.
- Fresh impacts expose ice excavated from 0.3-2.0 meters depth
- Dirty ice at polar locations: Estimated to be 90-100 wt% H_2O, mixed with dust from global dust storms

Recurring Slope Lineae (RSL)

- Briny water has been theorized as cause of RSLs.
- Located at equator-facing sunward-facing sides of craters/ridges in the 30° to 50° latitude range

Aquifers

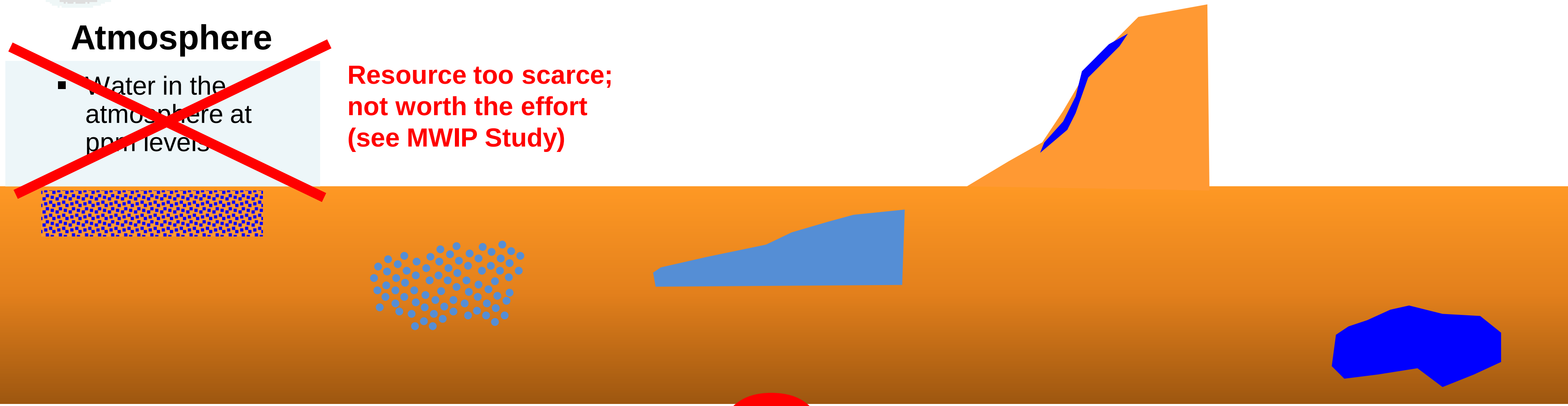
- Suspected to be >1 km below surface

Water on Mars
(Simplified)

Atmosphere

- Water in the atmosphere at ppm levels

Resource too scarce; not worth the effort (see MWIP Study)



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?

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Recurring Slope Lineae (RSL)

- Briny water has been theorized as cause of RSLs.
- Located at equator-facing sunward-facing sides of craters/ridges in the 30° to 50° latitude range
- **RSL sites and possibly the active gullies are Special Regions.**

Aquifers

- Suspected to be >1 km below surface
- **No evidence found for existence but would be considered a Special Region**

- **Not considered to be Special Regions unless heated to liquid state**

Mars Water-Based ISRU and Human Operations

- **EVA and habitat/rover operations in the human operating zone will expose the Mars surface to human contaminants from suit/habitat leakage, crew maintenance, imperfect hardware cleaning, etc.**
  - Region will be polluted so current robotic mission forward planetary protection rules can not apply to human operating zone
- **ISRU soil processing for water may occur in/near zones of human operation and habitats. ISRU soil excavation operations will:**
  - Bring subsurface material to the surface which could be distributed by wind toward astronauts and human habitats, rovers, etc. (back contamination)
  - Expose astronauts to subsurface material during maintenance (back contamination)
  - Allow surface human contaminants to reach material surfaces exposed underground; when operations occur during crew presence. (forward contamination into non-special region)
- **ISRU hydrated soil excavation and processing operations <u>Will Not</u> create Special Regions so forward contamination issues are mitigated**
  - Since soil reactors will most likely operate at >300 °C for >1 hour, there should be minimal concern about dumping processed soil.
- **ISRU water extraction for subsurface ice sheets could create temporary or long term Special Regions depending on the extraction technique**
  - Rodwell water extraction concept is most likely forbidden under current Planetary Protection rules

Mars Water ISRU and Planetary Protection Conclusion

Proposed rules/guidelines: ISRU excavation and soil processing can be performed on Mars as long as:

- The excavation devices and soil processing hardware are sterilized before launch;
  - This includes any water or other reactants that might be launched from Earth to support startup operations
- No *in situ* heating of soil where water will be or reside in liquid form for 'long periods' of time.
  - Duration of operation will need to be defined and approved before launch
- No *in situ* liquid water resources are used (subterranean aquifers or RSLs)
- Clean (ambient or artificial UV light, high pressure gas, and/or 'sand blast') hardware exposed to subsurface material before maintenance or transfer into habitat

Leakage of ISRU reactants and products may confuse search for life effort but will not cause planetary protection issues

Use of Rodwell concept for water extraction from a subsurface ice sheet may be permissible only if:

1) Previous sample analysis shows there is no sign of life
2) Planetary protection rules are changed once humans explore the surface of Mars due to uncontrollable forward contamination issues
3) A combination of #2 and #3

BACKUP

Special Regions (COSPAR)

1.1.2. Special Regions. COSPAR defines Special Regions as ‘‘a region within which terrestrial organisms are likely to replicate’’ and states that ‘‘any region which is interpreted to have a high potential for the existence of extant martian life forms is also defined as a Special Region’’ (COSPAR, 2011). At present there are no Special Regions defined by the existence of extant martian life, and this study concentrates only on the first aspect of the definition.

1.1.3. Non-Special Regions. A martian region may be categorized as Non-Special if the temperature and water availability will remain outside the threshold parameters posited in this study for the time period discussed below (see Section 1.4: Constraints). All other regions of Mars are designated as either Special or Uncertain.

1.1.4. Uncertain Regions. If a martian environment can simultaneously demonstrate the temperature and water availability conditions identified in this study, propagation may be possible, and those regions would be identified as Special Regions. Nonetheless, because of the limited nature of the data available for regions only sensed remotely, it may not be possible to prove that such environments are capable of supporting microbial growth. Such areas are therefore treated in the same manner as Special Regions until they are shown to be otherwise.

In the original study, the definition of **Special Region was determined by a lower temperature limit for propagation (which was given as - 20C, including margin) and a lower limit for water activity (with margin, an activity threshold of 0.5)**. The COSPAR Colloquium recommended that Special Regions be determined by a lower temperature limit for propagation of - 25C, which included additional margin and thus was slightly more conservative than the MEPAG SRSAG limit. Water activity or a_w is the partial vapor pressure of water in a substance divided by the standard state partial vapor pressure of water**.** Pure distilled water has a water activity of exactly one.

Recent gullies and gully forming regions, ‘‘pasted-on’’ mantle, low-latitude slope streaks, low-latitude features hypothesized to be glaciers, and features hypothesized to be massive subsurface ice—all of which were considered potentially Special Regions

Water Resources: SR-SAG 2 (1)

- **Equatorial Region (between 30°S and 30°N)**
  - Areas of H_2O enhancement (from Mars Odyssey neutron analysis) within equatorial region are usually interpreted as being due to hydrated minerals, which may contain water contents up to ~13%.
  - Ice deposits from past periods of high axial tilt remain at depth (>15 m) in localized regions, such as northwest of the Tharsis volcanoes.
  - Impact crater analysis, radar data, and neutron spectrometer data suggest that subsurface ice is generally located at depths >5 m in this region and often >50 m depth.
  - Recurrent Slope Lineae (RSL) sites and potential active gullies suggest presence of near-surface liquid in certain locations.
  - RSL sites and possibly the active gullies are Special Regions. Other locations are not Special.
  - Accessibility limitations: High levels of solar energy and warmest temperatures on the planet, but limited accessibility to H_2O.

- **Mid-Latitudes (30°-60° latitude)**
  - Geomorphic evidence of ice-related features emplaced during period of high axial tilt.
  - Geomorphic evidence of features produced by possible fluvial activity in past (gullies, layered deposits in craters, etc.)
  - Fresh impacts expose ice excavated from 0.3-2.0 meters depth.
  - Region where ice deposition can occur during periods of high axial tilt
  - RSL activity concentrated in this zone, particularly in southern hemisphere.
  - RSL sites are treated as Special Regions. Other regions in this zone not considered to be Special unless heated to melting or some future observation points to the natural presence of water.
  - Accessibility limitations: Energy produced by solar power limited to summer season

Water Resources: SR-SAG 2 (2)

- **High Latitudes (60° - 80° latitude)**
  - Region largely covered by seasonal caps during winter season
  - As seasonal caps retreat in spring, frost outliers (both CO_2 and H_2O) are left behind
  - Region surrounding north polar cap largely comprises the Vastitas Borealis Formation, interpreted as composed of ice-rich fine-grained (dust) deposits and ice-rich sediments from ancient fluvial activity.
  - Ice-rich fine-grained deposits also seen surrounding south polar cap, but much thinner than in north.
  - Geomorphic features in this region suggest ice-rich flow associated with glacial activity both today and in past
  - New fresh impacts in this region expose ice excavated from depths ranging from 0.3 m to 1.7 m.
  - Not considered to be Special Regions unless heated to melting
  - Accessibility Limitations: Same as polar caps

- **Polar caps (poleward of ~80° latitude)**
  - Seasonal caps are CO_2 ice.
  - Permanent south polar cap is H_2O covered by ~8 m thick veneer of CO_2 ice.
  - Permanent north polar cap is H_2O ice
    - ~3 km thick, 1100-km diameter
    - Volume estimated between 1.1 and 2.3 x 10^6 km^3. Freshwater content estimated to be ~100x the amount in North American Great Lakes.
    - Ice accessible at surface
    - Estimated to be 90-100 wt% H_2O, mixed with dust from global dust storms
  - Polar caps are not considered to be Special Regions unless heated to melting
  - Accessibility Limitations: Polar night darkness and cold limit useful season; CO_2 degassing in area may affect safe access by human explorers

ISRU State-of-the-Art: Resource Acquisition, Processing, Consumables Production

- Significant work has been performed to demonstrate feasibility of ISRU concepts and develop components and technologies (TRL 1-4)
  - Mars atmosphere collection, separation, and processing into O_2 or O_2/CH_4
  - Lunar regolith excavation, beneficiation, and processing to extract O_2
  - Civil engineering/soil stabilization

- Some development & testing has been performed at the system level (TRL 4-6)
  - **Moon** (Lab, Analog sites)
    - Regolith and Environment Science & Oxygen and Lunar Volatiles Extraction (RESOLVE)
    - Precursor ISRU Lunar Oxygen Testbed (PILOT) and ROxygen
  - **Mars** (Lab, Environment)
    - Portable Mars Production Plant (early ‘90s),
    - Mars Sabatier/Water Electrolysis System (Mars environmental chamber in 2000)
    - Mars In-situ Propellant Precursor (MIP) (flight experiment for cancelled Mars 2001 mission)
    - Mars Oxygen ISRU Experiment (MOXIE) scheduled to fly on Mars 2020 mission

- However, **<u>significant work is needed to mature these technologies</u>**
  - Develop & test much closer to full-scale for human mission needs
  - Demonstrate much longer operational durations
  - Validate performance under relevant environmental conditions
  - Demonstrate integration and operation between the many components and subsystems that comprise an ISRU system
  - Realize synergy between ISRU and other exploration elements such as propulsion, life support, power, surface mobility, thermal management, etc.

- **Scope: Develop the component, subsystem, and system technology to enable production of mission consumables from regolith and atmospheric resources at a variety of destinations**
  - Initial focus
    - Critical technology gap closure
    - Component development in relevant environment (TRL 5)
  - Interim Goals
    - ISRU subsystems tests in relevant environment (Subsystem TRL 6)
  - End-Goals
    - End-to-end ISRU system tests in relevant environment (System TRL 6)
    - Integrated ISRU-Exploration elements demonstration in relevant environment

Overall Goals

System-level TRL 6 to support future flight demonstration missions

Provide Exploration Architecture Teams with validated, high-fidelity answers for mass, power, and volume of ISRU Systems

Mars ISRU Propellant Production

Large Gap between Needs and Demonstrated

Needs

- **Propellant production for human mission ascent (Mars DRA 5.0)**
  - For O_2 only: 2.2 to 3.5 kg/hr O_2; 480 days or 300 days
  - For O_2/CH_4:
    - 0.55 to 0.88 kg/hr CH_4
    - 1.2 to 2.0 kg/hr H_2O; (41 to 66 kg/hr soil @ 3% H2O by mass)

- **Propellant production for Mars Sample Return**
  - 0.35 to 0.5 kg/hr O_2; 420 to 500 days (multiple studies)
  - 0.75 to 1.5 kg/hr O_2; 35 or 137 days (Mars Collaborative Study 4-2012)

- **Propellant production for Mars ISRU Demo**
  - 0.01 kg/hr O_2; 15 operations min. (MOXIE)
  - 0.00004 kg/hr O_2; 10 operations (MIP demo on Mars 2001 Surveyor)

Demonstrated

- **Mars ISRU Testbeds (late '90s early '00s):**
  - LMA/JSC Sabatier/Water Electrolysis: 0.02 kg/hr O_2; 0.01 kg/hr CH_4
  - KSC RWGS/Water Electrolysis 0.087 kg/hr O_2
  - Pioneer Astronautics (SWE & RWGS): 0.02 kg/hr O_2; 0.01 kg/hr CH_4
    (IMISPPS): 0.031 kg/hr O_2, 0.0088 kg/hr CH_4

- **Atmosphere Processing: MARCO POLO** (Individual subsystems)
  - CO_2 Collection: 0.088 kg/hr CO_2
  - CO_2 Processing: 0.066 kg/hr of O_2; 0.033 kg/hr of CH_4; 0.071 kg/hr of H_2O
  - Water Processing: 0.52 kg/hr H_2O; 0.46 kg/hr O_2

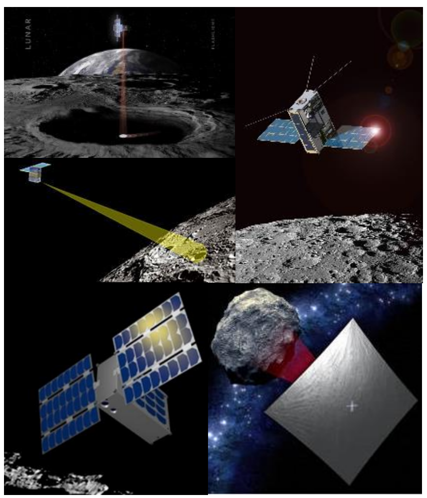
- **Soil Processing:**
  - Lunar H_2 Reduction - ROxygen Reactor: 5 to 10 kg/hr soil:
  - Lunar H_2 Reduction - PILOT Reactor: 4.5 to 6 kg/hr soil:
  - Mars Soil Auger - MISME: 0.18 to 0.2 kg/hr soil
  - Mars Soil Reactor-Pioneer Ast. Hot CO_2 4 kg/hr soil per batch

G. Sanders, (281) 483-9066, gerald.b.sanders@nasa.gov

Current NASA ISRU Missions Under Development

Resource Prospector – RESOLVE Payload

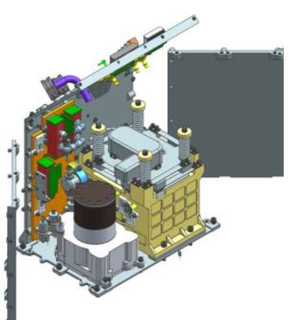
- Measure water (H_2O): Neutron spec, IR spec., GC/MS
- Measure volatiles – H_2, CO, CO_2, NH_3, CH_4, H_2S: GC/MS
- Possible mission in 2020



Cubesats (SLS EM-1 2018)

- Lunar Flashlight: Uses a Near IR laser and spectrometer to look into shadowed craters for volatiles
- Lunar IceCube: Carries the Broadband InfraRed Compact High Resolution Explorer Spectrometer (BIRCHES)

  LunaH-MAP: Carries two neutron spectrometers to produce maps of near-surface hydrogen (H)
- Skyfire: Uses spectroscopy and thermography for surface characterization
- NEA Scout: Uses a science-grade multispectral camera to learn about NEA rotation, regional morphology, regolith properties, spectral class



Mars 2020 ISRU Demo

- Make O_2 from Atm. CO_2: ~0.01 kg/hr O_2; 600 to 1000 W-hrs; 15 sols of operation
- Scroll Compressor and Solid Oxide Electrolysis technologies
- Payload on Mars 2020 rover